SURFACE-WATER HYDROLOGY OF HAY CREEK WATERSHED, MONTANA, AND WEST BRANCH ANTELOPE CREEK WATERSHED, NORTH DAKOTA

By Douglas G. Emerson

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4038

Prepared in cooperation with the

U.S. BUREAU OF LAND MANAGEMENT

Bismarck, North Dakota

1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Water Resources Division
821 East Interstate Avenue
Bismarck, ND 58501

Copies of this report can
be purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center, Bldg. 810
Box 25425
Denver, CO 80225

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS, Continued

TABLES

Page

CONVERSION FACTORS

For those readers who may prefer to use the International System (SI) of metric units rather than inch-pound units, the conversion factors for the terms used in this report are given below.

Multiply inch-pound unit	By	To obtain SI unit
Bar	100,000	pascal (Pa)
Cubic foot per second (ft^3 s)	0.02832	cubic meter per second (m^3/s)
Foot (ft)	0.3048	meter (m)
Foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
Inch (in.)	25.40	millimeter (mm)
Langley per day (Ly/d)	60,250	kilojoule per square meter day [$kJ/(m^2 \cdot d)$]
Langley per minute (Ly/min)	41,840	joule per square meter minute [$J/(m^2 \cdot min)$]
Mile (mi)	1.609	kilometer (km)
Millibar (mb)	0.1000	kilopascal (kPa)
Pound (lb)	0.4535	kilogram (kg)
Square foot (ft^2)	0.0929	square meter (m^2)
Square mile (mi^2)	2.590	square kilometer (km^2)
Ton per acre-foot	0.7355	kilogram per square meter (kg/m^2)
Ton per day	907.2	kilogram per day (kg/d)
Ton per square mile	350.3	kilogram per square kilometer (kg/km^2)

Temperature in degrees Celsius (°C) can be converted to temperature in degrees Fahrenheit (°F) by the formula °F = (°Cx1.8)+32 or to degrees Kelvin (°K) by the formula °K = °C+273.15.

SURFACE-WATER HYDROLOGY OF HAY CREEK WATERSHED, MONTANA, AND WEST BRANCH ANTELOPE CREEK WATERSHED, NORTH DAKOTA

By Douglas G. Emerson

ABSTRACT

Hydrologic data were used to determine the premining surface-water conditions in two small basins in the Fort Union coal region of Montana and North Dakota. The two streams, Hay Creek and West Branch Antelope Creek, are ephemeral. Most of the volume and peak discharges are due to snowmelt runoff. Little rainfall runoff occurs, and volume and peak discharges for this runoff are relatively small compared to those for snowmelt runoff.

Suspended-sediment concentrations for snowmelt runoff ranged from 4 to 325 milligrams per liter for the Hay Creek and West Branch Antelope Creek watersheds. At the outflow site of the Hay Creek watershed, the dominant dissolved constituents in runoff are magnesium and sulfate; at the outflow site of the West Branch Antelope Creek watershed, they are calcium, magnesium, bicarbonate, and sulfate.

The U.S. Geological Survey's Precipitation-Runoff Modeling System was calibrated for both watersheds for the snowmelt runoff. The model was not calibrated for rainfall runoff because of insufficient runoff. Sensitivity analyses indicated the model was most sensitive to the values of snow correction for daily precipitation at precipitation gages, emissivity of the air for longwave radiation, and maximum available water-holding capacity of the soil profile. Testing of several watershed delineations showed that, for well-defined snow distribution, 23 units adequately defined the variability in runoff in the Hay Creek watershed, and 36 units adequately defined the variability in runoff in the West Branch Antelope Creek watershed.

INTRODUCTION

In response to the U.S. Department of the Interior's call for leasing nomination of Federal coal land, eligible tracts were submitted by mining concerns for consideration of their leasing potential. The U.S. Bureau of Land Management has the responsibility of evaluating the leasing applications for mining of Federal coal. Their evaluation must address potential environmental impacts of mining, which include those related to hydrology. The U.S. Office of Surface Mining Reclamation and Enforcement (1977) provisions outline impacts in terms of the probable hydrologic consequences of the mining and reclamation operations both on and off the proposed permit area and the reasonable assessment of the probable cumulative impacts of mining. These impacts include changes in flow regimes, flood peaks and volumes, sediment yields, water quality, soil-water relations, and water-balance relations for watersheds before, during, and after mining.

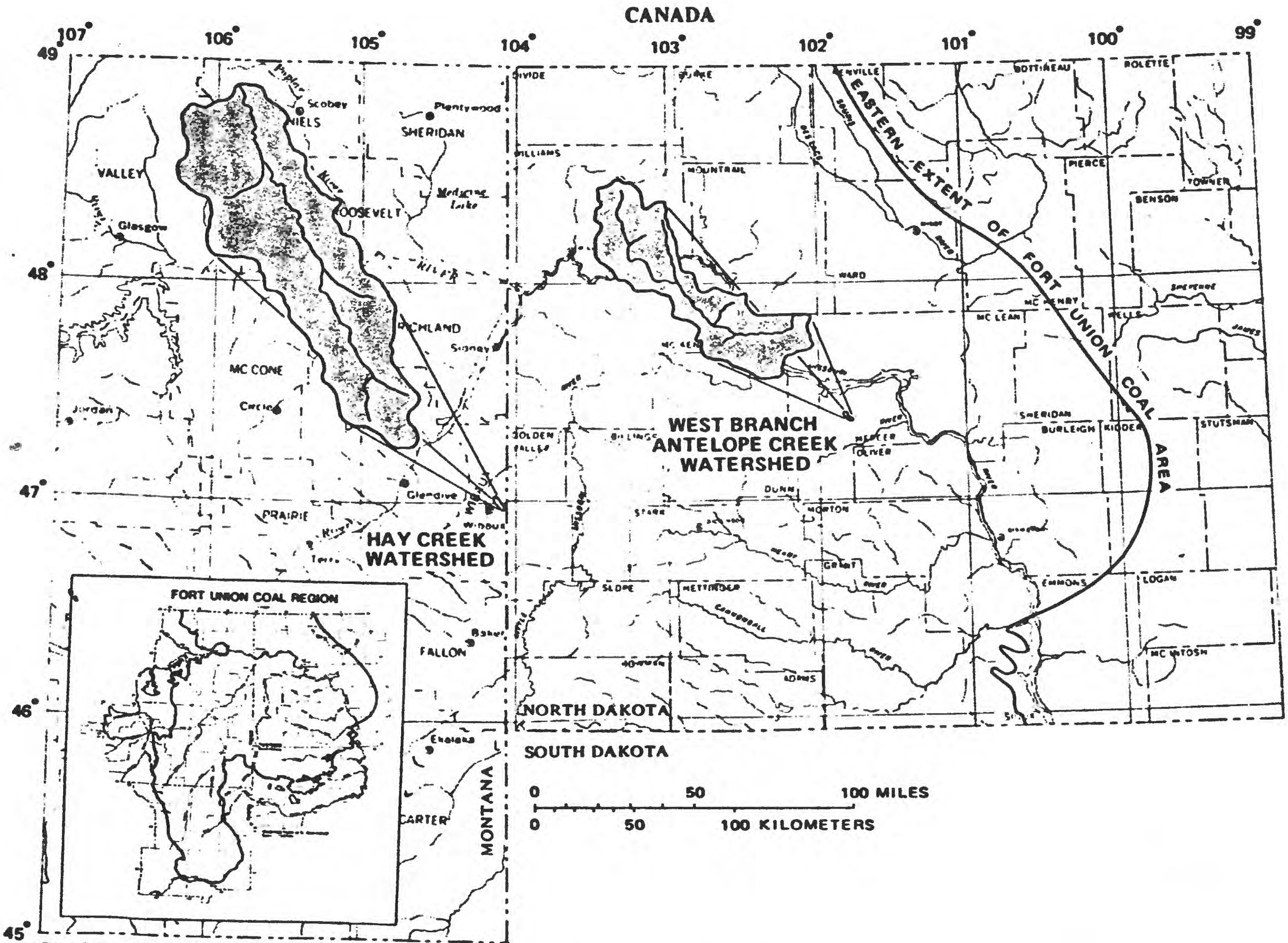
Purpose and Scope

In 1977, the U.S. Geological Survey began an investigation in cooperation with the U.S. Bureau of Land Management on the surface-water hydrology of two watersheds in the Fort Union coal region in eastern Montana and western North Dakota (fig. 1). The purpose of the investigation was to provide a means for U.S. Bureau of Land Management personnel and others to assess the impacts on surface-water hydrology due to changes in land use. The objectives were to: (1) Determine premining hydrologic conditions in two small, representative watersheds and, thus, provide historical data with which to compare the magnitude of changes during and after mining, and (2) develop and calibrate a watershed model that could be used to make reasonably accurate projections of effects on surface-water hydrology resulting from the various land treatments required for mining and reclamation.

The complexity of watershed hydrology limits the capability of analyzing all the seasonal changes. Hines and others (1975) discussed the importance of recognizing critical periods. First, in many watersheds there exists a particular period, controlled by cyclical hydrologic events, for which data analysis and model application can be aimed, thereby reducing the components of a watershed model. Second, the recurrence probability of a seasonal hydrologic event commonly can be evaluated statistically because these events often recur on a cyclical basis. This probability can be related to the results of the model predictions. Third, data needs for calibration of the watershed model are reduced. Analysis is greatly simplified if sampling is needed only for a short period of the year. Because of these advantages, the critical-period rationale has been used for data analysis and model application.

One purpose of this report is to document the kinds and quantity of data required and methods used to adequately define the surface-water hydrology of a watershed in the Fort Union coal region. The report defines the major hydrologic processes and the factors that affect them in regard to high- and low-flow conditions, erosion, and chemical quality. The report also contains the analysis of hydrologic processes and factors used to determine the critical runoff periods for the Hay Creek and West Branch Antelope Creek watersheds (fig. 1). The controlling processes in the Fort Union coal region vary from other areas. A discussion of these processes and many basic concepts is included to help the reader understand their importance in the Fort Union coal region.

Another purpose of the report is to provide documentation and calibration of a digital watershed model under premining conditions. The hydrologic system of the Hay Creek and West Branch Antelope Creek watersheds was simulated with the Precipitation-Runoff Modeling System developed by Leavesley and others (1983). Calibration of the model was performed for snowmelt runoff. The model was not calibrated for rainfall runoff because of the lack of rainfall runoff.



Base from U.S. Geological Survey

Figure 1.—Location of watersheds.

Description of Watersheds

The Hay Creek watershed is an 11.41-mi^2 watershed in Wibaux County in east-central Montana (fig. 1). The location and number of data-collection sites in and near the watershed are illustrated in figure 2. Most of the watershed is characterized by rolling topography devoted to pasture and the production of small-grain crops. The geology, climatology, topography, and ground-water hydrology of the area are discussed in detail by Horak (1983). There currently (1986) is no commercial production of lignite in the Hay Creek area.

The West Branch Antelope Creek watershed is an 8.46-mi^2 watershed in Mercer County in west-central North Dakota. The location and number of data-collection sites in and near the watershed are illustrated in figure 3. The watershed is one of rolling topography devoted largely to pasture and to the production of small-grain crops. The geology, climatology, topography, and ground-water hydrology of the area are discussed in detail by Crawley and Emerson (1981). Coal mining and agriculture are the chief economic activities.

Surface-water discharge and water-quality data were collected for streams in each watershed from 1977 to 1982. Data also were collected for a complete weather station at one site within each watershed and for additional precipitation stations located in and adjacent to the two watersheds. The data used in this report are published in a report by Emerson and others (1983).

HIGH FLOW

The major processes that affect high flow can be divided into three groups--water availability, water excess, and water routing (table 1). "Water availability" makes water available to begin runoff from the watershed. "Water excess" decreases the quantity of water from that which is available to that which is in excess and actually runs off. "Water routing" determines the direction and speed that the excess water runs off. A brief review of the processes and the factors that affect them is given in the following sections.

Water Availability

The temporal and areal variations in the quantity of precipitation from a rainstorm are determined by the meteorological conditions of that rainstorm. Rainstorms that have potential of producing high flow are cellular in their spatial structure. The increase and decrease of both the size and intensity of these cells and the movement of the cell system will determine the temporal and spatial variations of the rainstorm. The variability of rainfall over an area is a function of the storm duration, total rainfall depth, storm type, and size of the area under consideration.

The snowmelt process is complex and its influence on runoff is not easily characterized in an analysis. Detailed descriptions of the snowmelt process are given by the U.S. Army Corps of Engineers (1956) and Eagleson (1970, p. 243-259). The process and factors that affect high flows caused by

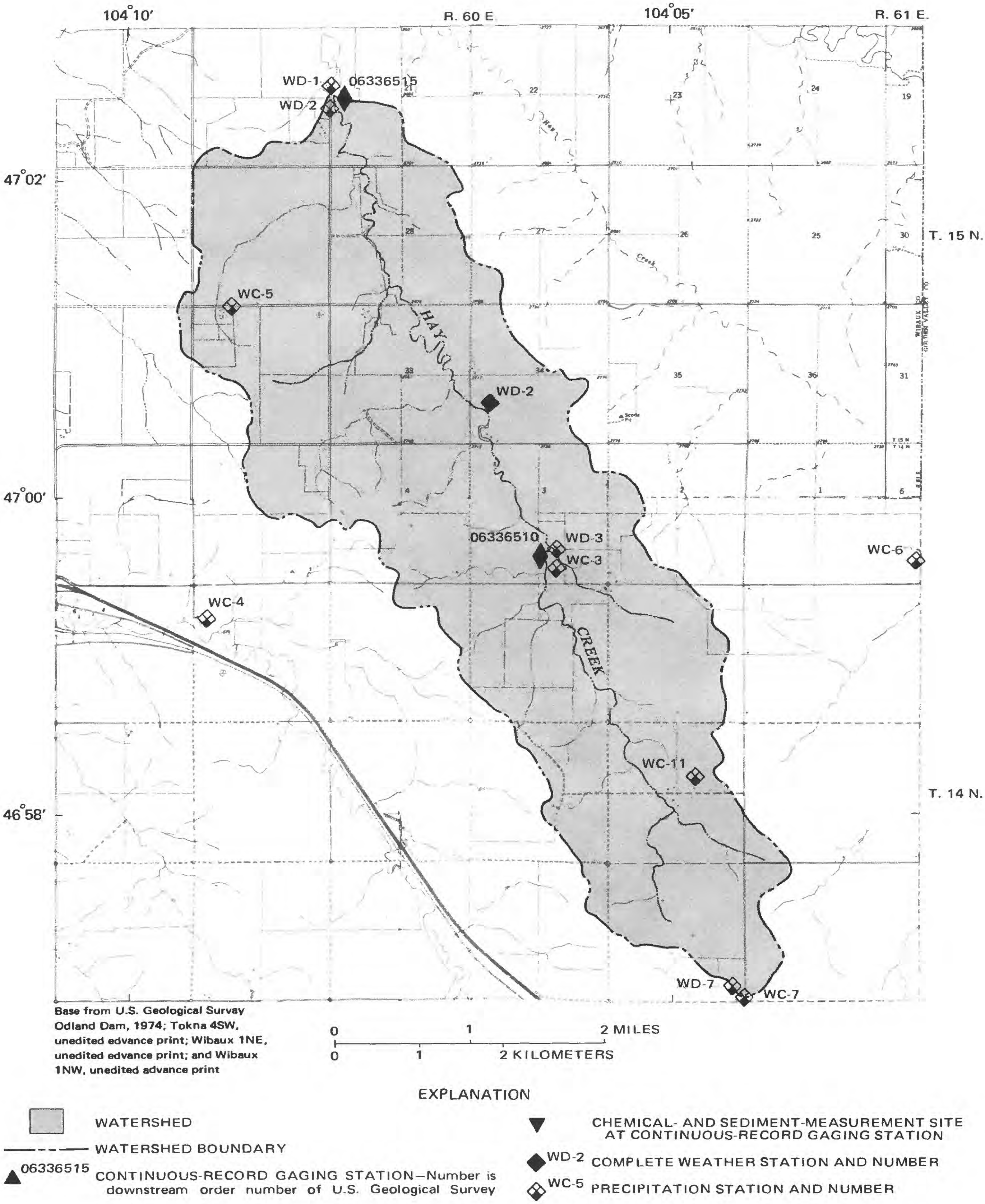
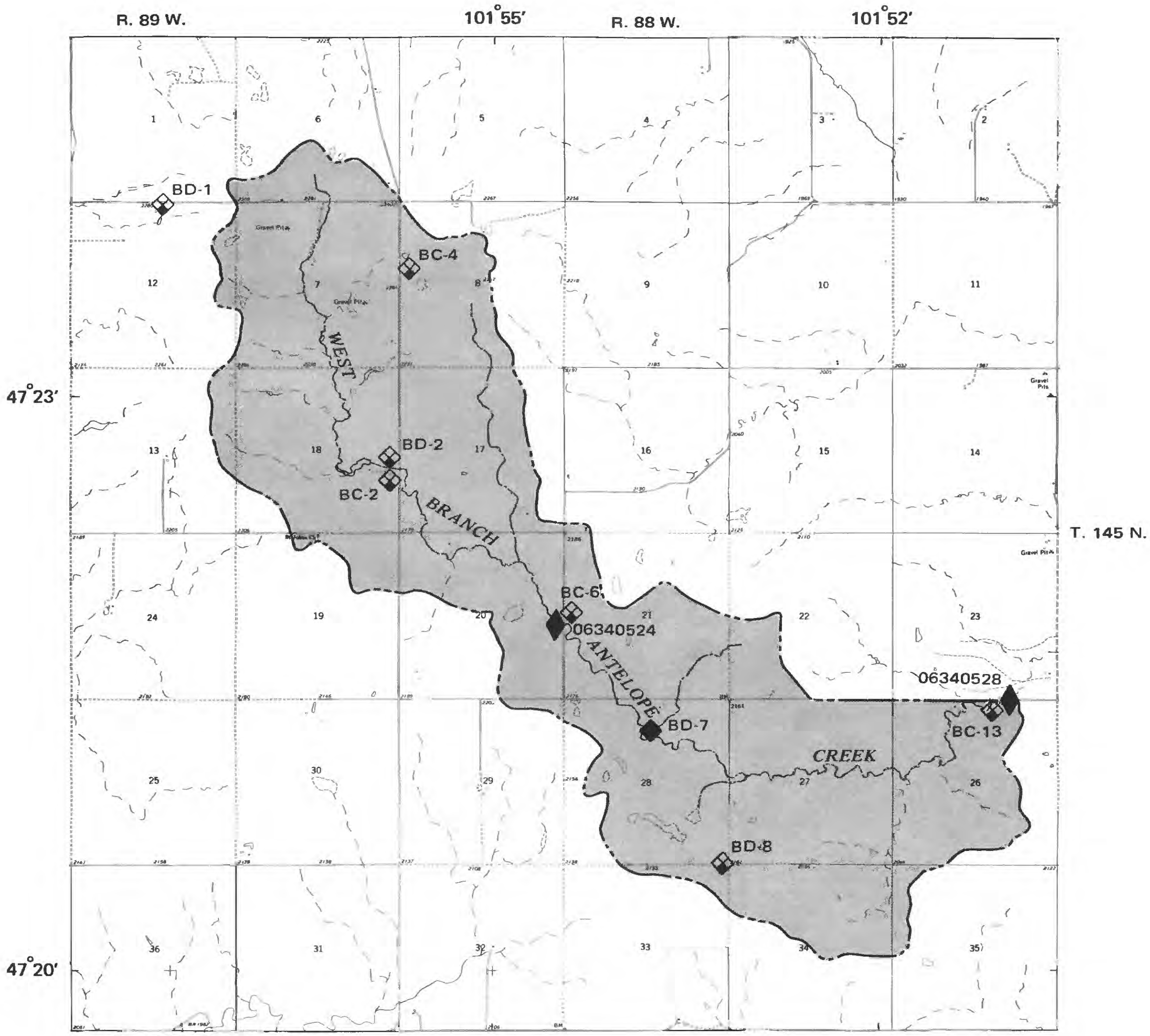


Figure 2.—Data-collection sites in the Hay Creek watershed and vicinity.



Base from U.S. Geological Survey
Beulah NW, 1969; Beulah, 1968;
Beulah NE, 1969; Zap, 1969

0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

WATERSHED

WATERSHED BOUNDARY

▲06340528 CONTINUOUS-RECORD GAGING STATION—Number is downstream order number of U.S. Geological Survey

▼ CHEMICAL- AND SEDIMENT-MEASUREMENT SITE AT CONTINUOUS-RECORD GAGING STATION

◆BD-7 COMPLETE WEATHER STATION AND NUMBER

BC-4 PRECIPITATION STATION AND NUMBER

Figure 3.—Data-collection sites in the West Branch Antelope Creek watershed and vicinity.

Table 1.-- *Hydrologic processes that control high flow and factors affecting the processes*

[Modified from Miller and Frink, 1982, p. 20]

Hydrologic processes	Factors affecting the processes
Water availability	
Rainfall	Temporal and areal variability
Snowmelt	Antecedent
	Areal variability of snowpack
	Vegetation, exposure
	Snowpack temperature
	Snowpack density
	Snowpack air and water content and heat-transfer and storage properties
	Formation of ice planes
	Soil temperature
	Melt period
	Solar radiation
	Air temperature
	Wind velocity
	Rainfall
	Longwave radiation
	Dewpoint temperature
Water excess	
Infiltration	Antecedent
	Soil type
	Soil condition
	Soil moisture
	Extent to which soil is frozen
	Vegetation
	Ground-water level
	Soil-moisture-excess period
	Moisture-availability rate

Table 1.-- *Hydrologic processes that control high flow and factors affecting the processes*--Continued

Hydrologic processes	Factors affecting the processes
	<u>Water excess, Continued</u>
Evapotranspiration	Meteorological
	Solar radiation
	Wind velocity
	Air temperature
	Water temperature
	Humidity
	Plant and soil
	Vegetation type
	Vegetation growth
	Soil moisture
	Soil capillary characteristics
	Soil type
Depressional storages	Soil type
	Terrain
Interception	Vegetation density and type
	Till practices
	Precipitation type
	Wind
	<u>Water routing</u>
Overland flow	Basin slope
	Vegetation
Depressional storages	Percentage of storage already filled
	Contributing drainage area
	Ground-water level
Interflow	Hydraulic connection of moisture excess/interflow conduits/ drainage channels

Table 1.-- *Hydrologic processes that control high flow and factors affecting the processes*--Continued

Hydrologic processes	Factors affecting the processes
	Water routing, Continued
Ground-water flow	Hydraulic connection of moisture excess/ground water/drainage channels
Channel flow	Antecedent Channel-storage level Channel-vegetation condition Runoff Channel slope Channel geometry Backwater conditions
Overbank storages	Stream-valley shape Channel capacity Backwater conditions
Reservoir storages	Percentage of storage already filled Contributing drainage area

snowmelt are included in table 1. There are a number of both antecedent and melt-period factors that affect the quantity of water released and the rate at which the water is released to begin the runoff. Compared to rainfall runoff very little research has been done on snowmelt runoff. Only during the last few decades has intensive research resulted in the application of the theory that explains the complex processes producing snowmelt and sequential runoff. Lack of research is partly due to the complex factors that affect the processes. This lack makes analysis of snowmelt runoff very difficult and, therefore, makes analysis of the watersheds difficult because 85 to 95 percent of the total annual runoff is snowmelt.

Water Excess

Water-excess processes are those processes that affect the quantity of water and the rate at which the water becomes excess and runs off. These processes and the factors that affect them are listed in table 1 and are described in detail by Eagleson (1970).

If the surface is permeable, part of the available water will infiltrate into the soil by gravity and capillary forces. The antecedent factors determine the quantity and rate of water that is capable of infiltrating. The factor that affects the soil-moisture-excess period is the moisture-availability rate. The wilting point and field capacity are two measurements of soil moisture that are used in determining infiltration. Wilting point is the soil-moisture content when plants permanently wilt, and field capacity is the quantity of water that can be stored in a soil after excess water has drained away.

To predict snowmelt runoff from terrain, the redistribution of soil moisture that occurs during the winter and the infiltration properties of the soil at the time of ablation need to be known. Existing hydrologic-modeling techniques have not properly accounted for changes in soil moisture beneath snow cover or under frozen-ground conditions. Studies have shown that, during freezing conditions, soil moisture migrates toward the freezing front from the deeper warm soils (Peck, 1974, and Kane, 1981). The quantity of water movement is greater for wet soils than dry soils. This migration has the net effect of increasing the soil moisture near the ground surface. With greater ice content at the ground surface, the infiltration rate is reduced, increasing the potential quantity of runoff. Kane (1981) found that infiltration rates for wet, frozen Fairbanks silt loam were two orders of magnitude less than those for relatively dry, frozen soils. Infiltration rates for dry, frozen soil were slightly less than those for unfrozen soil.

Evapotranspiration is the combined processes of evaporation and transpiration. Evaporation is defined as the process by which a liquid or a solid is changed into a gas. Transpiration is defined as the process by which water vapor escapes from living plants. Evapotranspiration is controlled by meteorological factors and plant and soil factors. The relative importance of each of the numerous factors generally is difficult to assess.

Water retained in puddles, ditches, and other depressions in the soil surface is known as depressional storage. These depressions vary in magnitude from the size of soil particles to large puddles. As soon as rainfall intensity at the soil surface exceeds the infiltration rate, the rainfall excess begins to fill surface depressions. The following conditions need to be recognized to understand the sequence of events following the beginning of rainfall excess (Linsley and others, 1949, p. 269):

(1) Each depression has its own capacity or maximum depth.

(2) As each depression is filled to capacity, further inflow is balanced by outflow plus infiltration and evaporation.

(3) Depressions of various sizes are both superimposed and interconnected.

(4) Each depression, until such time as it is filled, has a definite drainage area. Water held in depressions at the end of rain is either evaporated or absorbed by the soil through infiltration.

The part of precipitation that is stored on the vegetative cover is known as interception. The leaf system temporarily stores the rainfall, usually transforming the original raindrops to larger drops. In the meantime, the films and drops on the leaves are freely exposed to evaporation. Once the interception storage is filled, the quantity of water reaching the ground is equal to the rainfall less the evaporation from interception storage. The interception of snowfall by a conifer forest can be significant. The conifer canopy can retain a sizable quantity of the falling snow, keeping it from immediately reaching the ground. This intercepted snow then is exposed on all sides to evaporation losses.

Water Routing

Water-routing processes are those processes that determine the direction and speed at which the excess water runs off a watershed. The four major controlling processes of water routing are overland flow, which can be intercepted by depressional storages; interflow; ground-water flow; and channel flow, modified by bank, overbank, and reservoir storage. The processes and the factors that affect them are listed in table 1. Water routing is described in detail by Chow (1959), Henderson (1966), and Eagleson (1970).

Whenever and wherever the rate of rainfall or snowmelt exceeds the infiltration rate at the land surface, the excess water begins to accumulate in depressional storage. When the depressional-storage capacity is exceeded, surface runoff begins a thin sheet flow known as overland flow. The process of overland flow is complex and difficult to evaluate. Overland flow may be turbulent or laminar depending on such factors as discharge, slope, viscosity, and surface roughness. If velocities and depths of flow are relatively small, the viscosity dominates and the flow is laminar. Uniform overland flow becomes turbulent if the surface is rough and if the depth of flow is sufficient to produce persisting eddies. In this case, surface roughness is dominant.

Interflow is the part of water that infiltrates the soil surface and moves laterally through the upper soil horizon toward the streams. The processes of interflow are not well understood.

Ground-water flow is the part of runoff that has passed into the ground due to deep percolation of infiltrated water, has reached the saturated zone, and has been discharged into a stream.

Overland flow, interflow, and base flow are combined as channel flow for routing. The routing process is defined by the equation of motion and the conservation of mass equation. The formulation of these equations can vary in complexity depending on what assumptions are made. Bank, overbank, and reservoir storage can greatly modify channel flow.

High-Flow Analyses

The peak flows that have been recorded by the stream-gaging stations in the two watersheds are listed in table 2. Of the total number of annual peaks (largest instantaneous discharge during a water year), 2 were due to rainfall runoff and 15 were due to snowmelt runoff. Of all the peaks--partial-duration and annual--6 were due to rainfall runoff and 19 were due to snowmelt runoff.

Table 2.-- *Recorded peak discharges in the Hay Creek and West Branch Antelope Creek watersheds*

Station number	Date	Discharge (cubic feet per second)	Type of runoff	Type of peak
		Hay Creek watershed		
06336510	3/19/78	85	Snowmelt	Annual
	7/05/78	14	Rainfall	Partial
	4/09/79	10	Snowmelt	Annual
	3/15/80	4	Snowmelt	Annual
	2/15/81	14	Snowmelt	Annual
06336515	3/19/78	50	Snowmelt	Annual
	6/29/78	16	Rainfall	Partial
	3/24/79	35	Snowmelt	Partial
	4/01/79	25	Snowmelt	Partial
	4/09/79	58	Snowmelt	Annual
	3/18/80	.6	Snowmelt	Annual
	2/15/81	37	Snowmelt	Annual
	6/20/81	18	Rainfall	Partial
	8/01/81	10	Rainfall	Partial
		West Branch Antelope Creek watershed		
06340524	3/26/78	125	Snowmelt	Annual
	4/17/79	435	Snowmelt	Annual
	3/18/80	11	Snowmelt	Annual
	2/16/81	39	Snowmelt	Annual
06340528	6/15/77	36	Rainfall	Annual
	3/26/78	122	Snowmelt	Annual
	4/11/79	35	Snowmelt	Partial
	4/17/79	650	Snowmelt	Annual
	3/18/80	21	Snowmelt	Annual
	2/16/81	30	Snowmelt	Partial
	9/05/81	99	Rainfall	Annual

Partial-duration peaks are instantaneous peaks greater than a predetermined discharge such that an average of three peaks will occur per year. Although this is a small sample for making any substantial conclusions, the data so far indicate that if high flow is critical, snowmelt needs to be considered the more critical period for the Fort Union coal region in Montana and North Dakota.

A more substantial comparison was made between the number of annual peaks due to snowmelt and the total number of annual peaks. A ratio of the number of annual peaks due to snowmelt to the total number of annual peaks (a ratio of 1.0 would indicate 100 percent of the annual peaks were due to snowmelt) was compiled from all the U.S. Geological Survey stations that: (1) Are located in the Fort Union coal region of North Dakota (except those stations located in the Badlands area, which appear to have different hydrologic characteristics); (2) are nonregulated; and (3) have 10 or more years of record. The mean of these ratios is 0.61, and the standard deviation is 0.17. A plot (fig. 4) of these ratios versus the drainage area for those stations shows no significant variation with the size of drainage area.

Rainfall Runoff

Rainfall-runoff analysis for the watersheds is limited because few rainstorms produced significant runoff. Based on the discharge magnitudes at selected exceedance probabilities at the sites as established by regression equations developed by Crosby (1975) (table 3), all of the rainfall-runoff peaks recorded had an exceedance probability greater than 50 percent.

A complete division of the quantity of water available and in excess from rainstorms is not warranted because only a few, minor rainstorms are available for analysis and because too many of the water-excess processes cannot be determined sufficiently. Therefore, a general analysis is appropriate. The temporal and spatial distribution of rainfall for the storm on June 29, 1978, in the Hay Creek watershed is shown in figure 5. The temporal variability is not significant--the starting and ending times of the major part of the storm at precipitation station WD-1 were 1045 and 1115 hours, the times for station WD-2 were 1015 and 1115 hours, and the times for station WD-3 were 1015 and 1100 hours. The spatial variation of the rainfall is significant. Station WD-1 recorded the least precipitation, 0.50 in., and station WC-6 recorded the most precipitation, 2.00 in.--a significant difference.

The runoff recorded at station 06336515 for the June 29, 1978, rainstorm also is shown in figure 5. The time from the start of precipitation (1015 hours) to the time runoff peaked (1645 hours) totaled 6.5 hours, a relatively long time for a short-duration rainstorm on a small basin. The rising limb of the hydrograph is uneven and elongated and the falling limb is elongated.

No runoff data are available for the storm on July 4, 1978, in the Hay Creek watershed to compare temporal variation. The spatial variation of the precipitation is shown in figure 6.

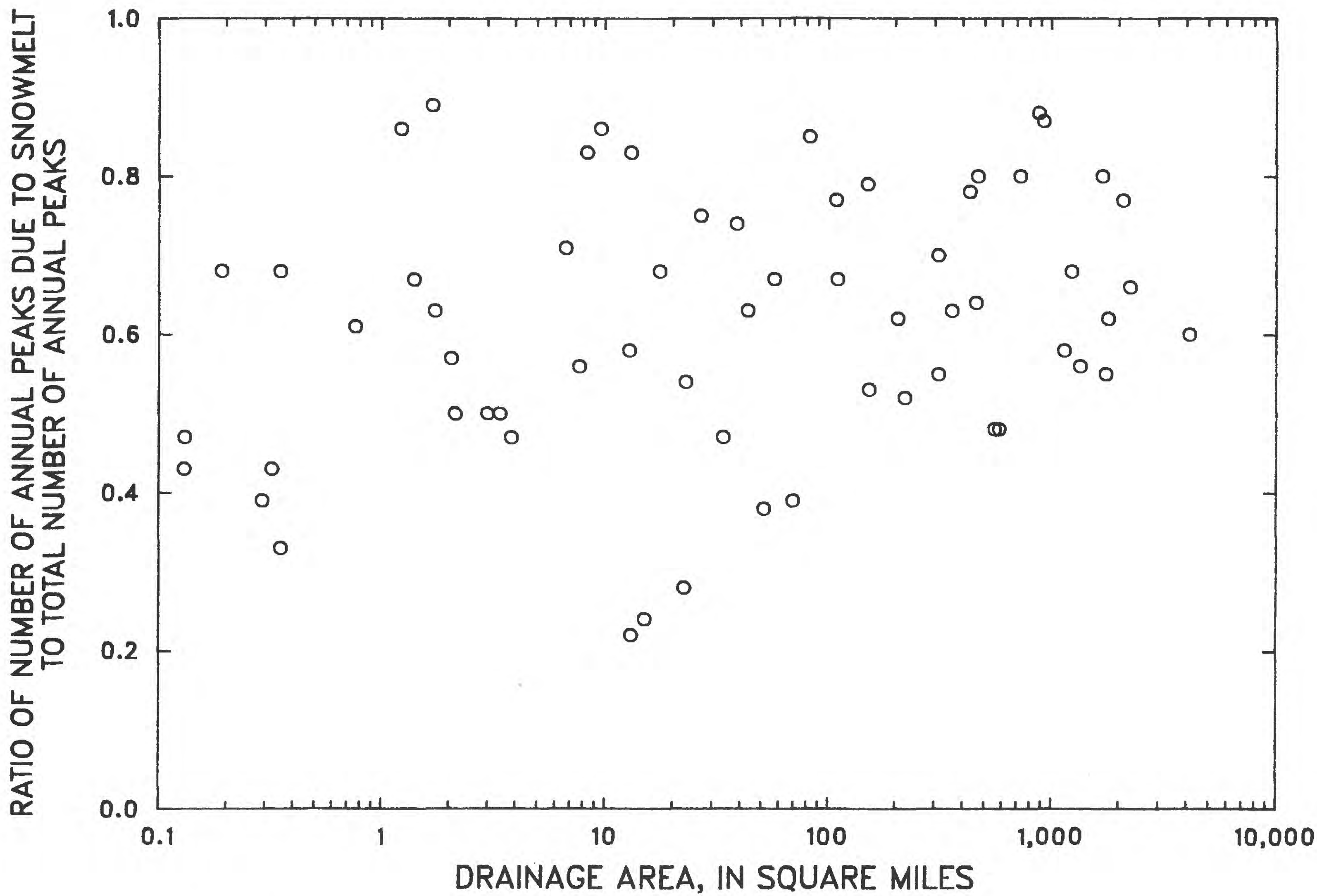


Figure 4.—Snowmelt-peak ratios versus drainage area from selected U.S. Geological Survey stream-gaging stations in the Fort Union coal region, North Dakota.

Table 3.-- *Magnitude and frequency of peak discharges in the Hay Creek and West Branch Antelope Creek watersheds*[1/]

Station	Area (square miles)	Soil-infiltration index	Peak discharge (cubic feet per second) for indicated exceedance probabilities (percent)				
			50	20	10	4	2
		Hay Creek watershed					
06336510	4.12	3.2	60	165	265	425	565
06336515	11.41	3.2	110	315	510	820	1,100
		West Branch Antelope Creek watershed					
06340524	4.37	3.0	70	190	300	480	630
06340528	8.46	2.8	120	325	515	800	1,050

[1/]Crosby, 1975, 24 p.

For the storm on June 15, 1977, in the West Branch Antelope Creek watershed, no rainfall data were available in the study basin. Therefore, no comparison of the rainfall to the runoff can be made.

The temporal and spatial distribution for the storm on September 5, 1981, in the West Branch Antelope Creek watershed is shown in figure 7. The temporal variability is not significant--the starting and ending times of the major part of the storm for both stations BD-2 and BD-7 were 2100 and 2145 hours. The spatial variation of the rainfall is not significant. Station BC-6 recorded the least precipitation, 1.15 in., and station BD-7 recorded the most precipitation, 1.6 in.--a difference of 28 percent.

The runoff recorded at gaging station 06340528 for the September 5, 1981, rainstorm also is shown in figure 7. The time from the start of precipitation (2045 hours) to the time runoff peaked (2245 hours) totaled 2 hours, a relatively short time. The rising and falling limbs of the hydrograph are steep.

A comparison of the rainfall quantity to the rainfall duration in the two study watersheds is shown in figure 8. All rainstorms with 0.30 in. or more of precipitation are plotted. The type of symbol indicates whether that

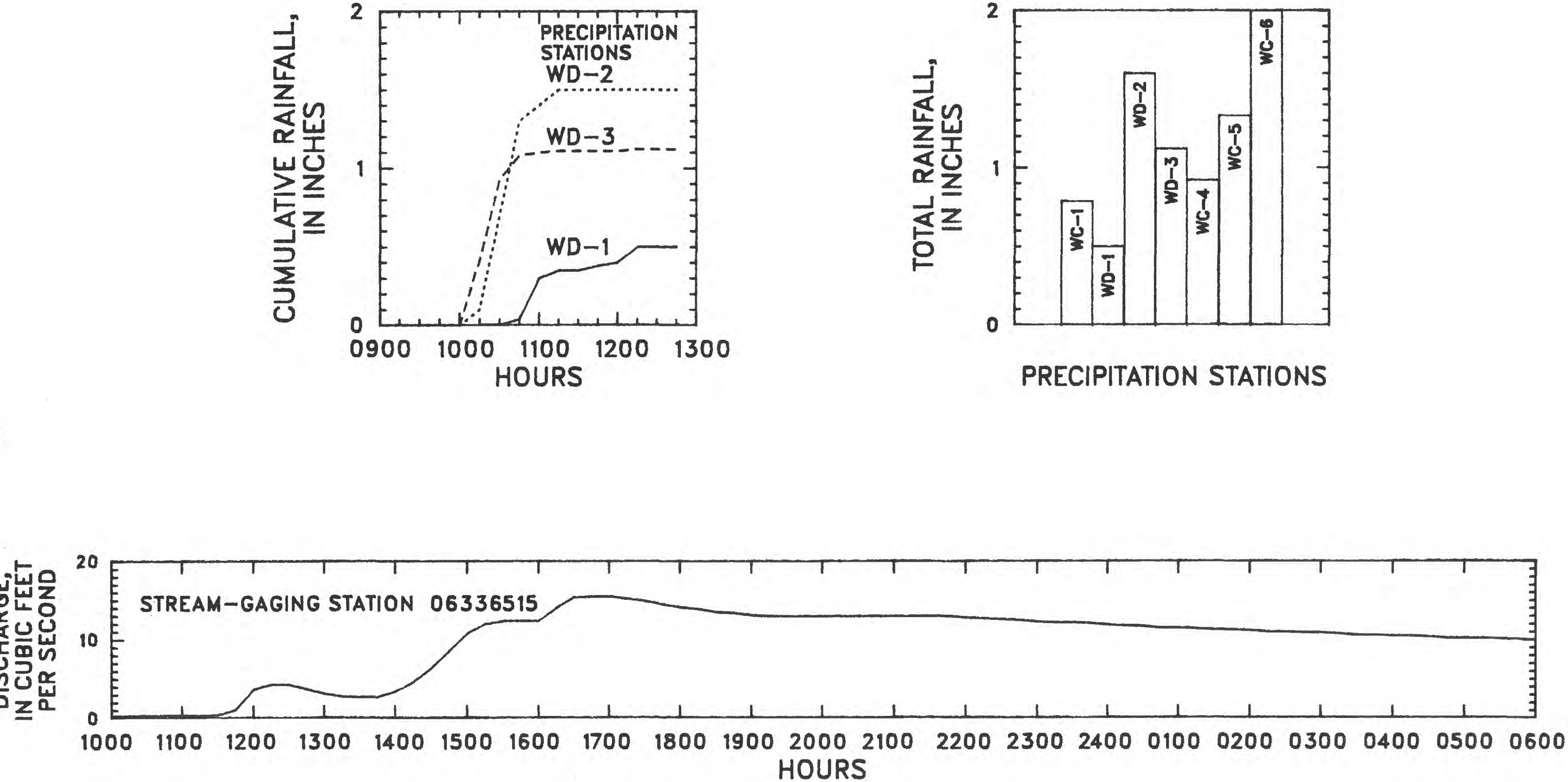


Figure 5.—Cumulative and total rainfall, and stream discharge of rainstorm in the Hay Creek watershed and vicinity on June 29, 1978.

rainstorm produced less than 0.5 or greater than 0.5 ft^3/s runoff. Although several rainstorms in each basin did produce runoff, only those storms discussed previously had any appreciable runoff. These plots give a general indication of how water-excess processes determine runoff. The duration is measured for the length of a storm and may not be a good representation of the storm's intensity, as can be noted in the September 5, 1981, rainstorm in the West Branch Antelope Creek watershed. In figure 8 the duration is plotted at 14 hours, but, as shown in figure 7, most of the rain fell in about 3/4 hour.

The factors that affected the infiltration process probably were quite similar for the June 29 and July 4, 1978, storms in the Hay Creek watershed. The soil type and vegetation cover were the same and the soil condition and soil-moisture content probably were quite similar because a rainstorm occurred 5 days before the June 29 storm and the June 29 storm occurred 6 days before the July 4 storm. Therefore, the antecedent soil condition and soil-moisture content should have been similar.

The evapotranspiration preceding the two storms is not known due to lack of relative-humidity data. For June 29, the maximum air temperature was 23.5 °C and the minimum was 12.0 °C. For July 4, the maximum air temperature was 29.0 °C and the minimum was 11.5 °C.

Depressional storages and interception should have been similar for the two storms. None of the factors controlling these processes should have changed because the farmers were finished with their spring fieldwork.

Water routing probably had a significant effect on the runoff from the two storms. For overland flow, the slope and vegetation cover did not change. However, the roughness/depth relationship could have changed very easily for the July 4 storm due to the runoff of the June 29 storm. Interflow should have negligible effect because the soils were found to be very tight.

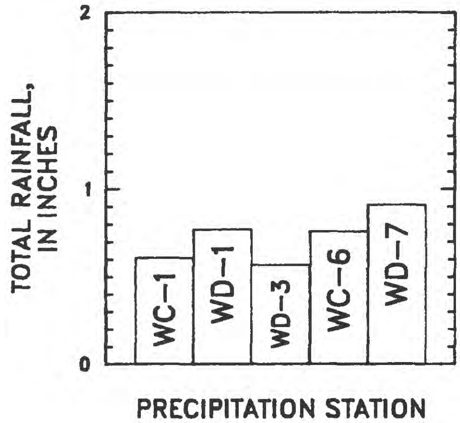


Figure 6.—Total rainfall of rainstorm in the Hay Creek watershed and vicinity on July 4, 1978.

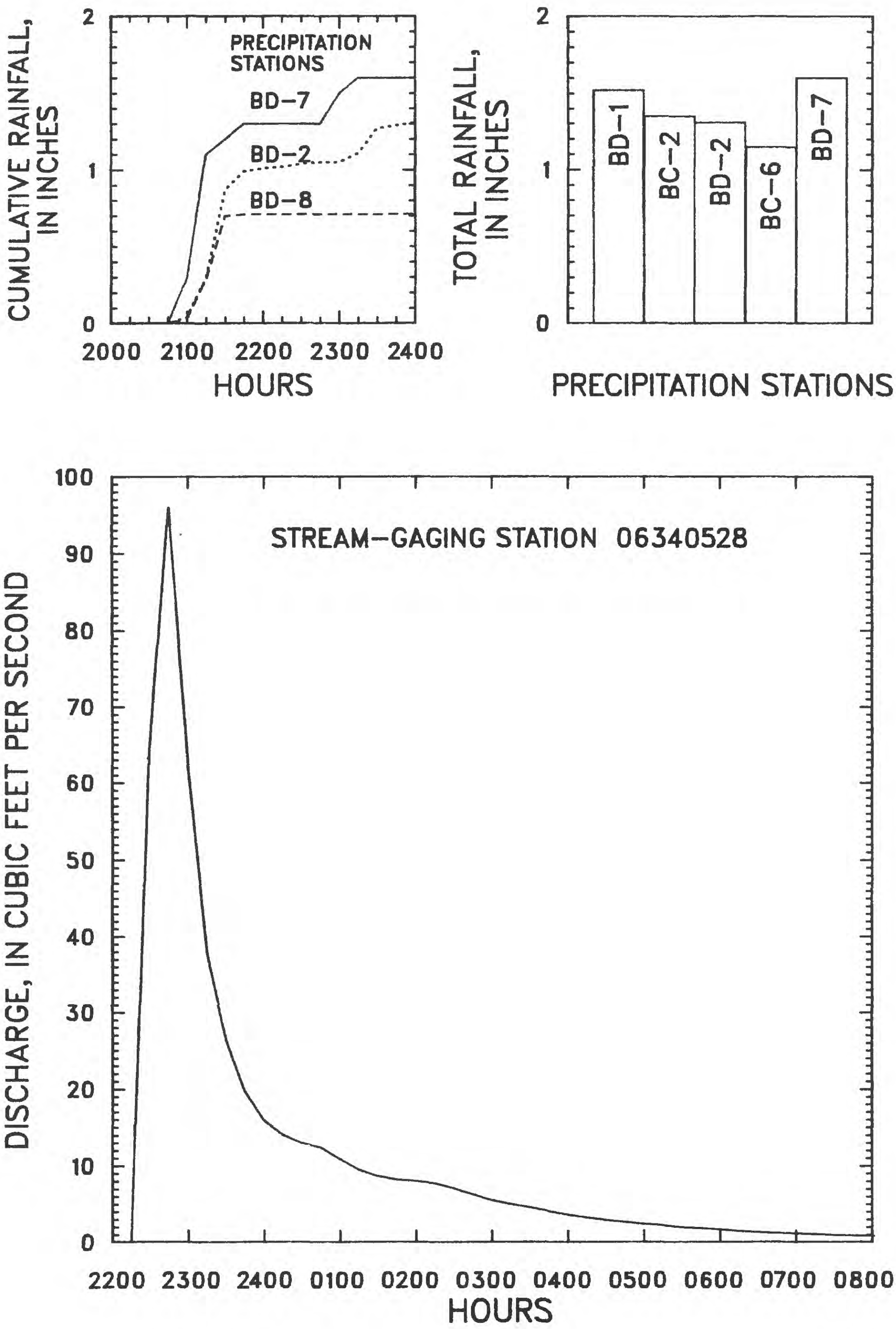


Figure 7.—Cumulative and total rainfall, and stream discharge of rainstorm in the West Branch Antelope Creek watershed and vicinity on September 5, 1981.

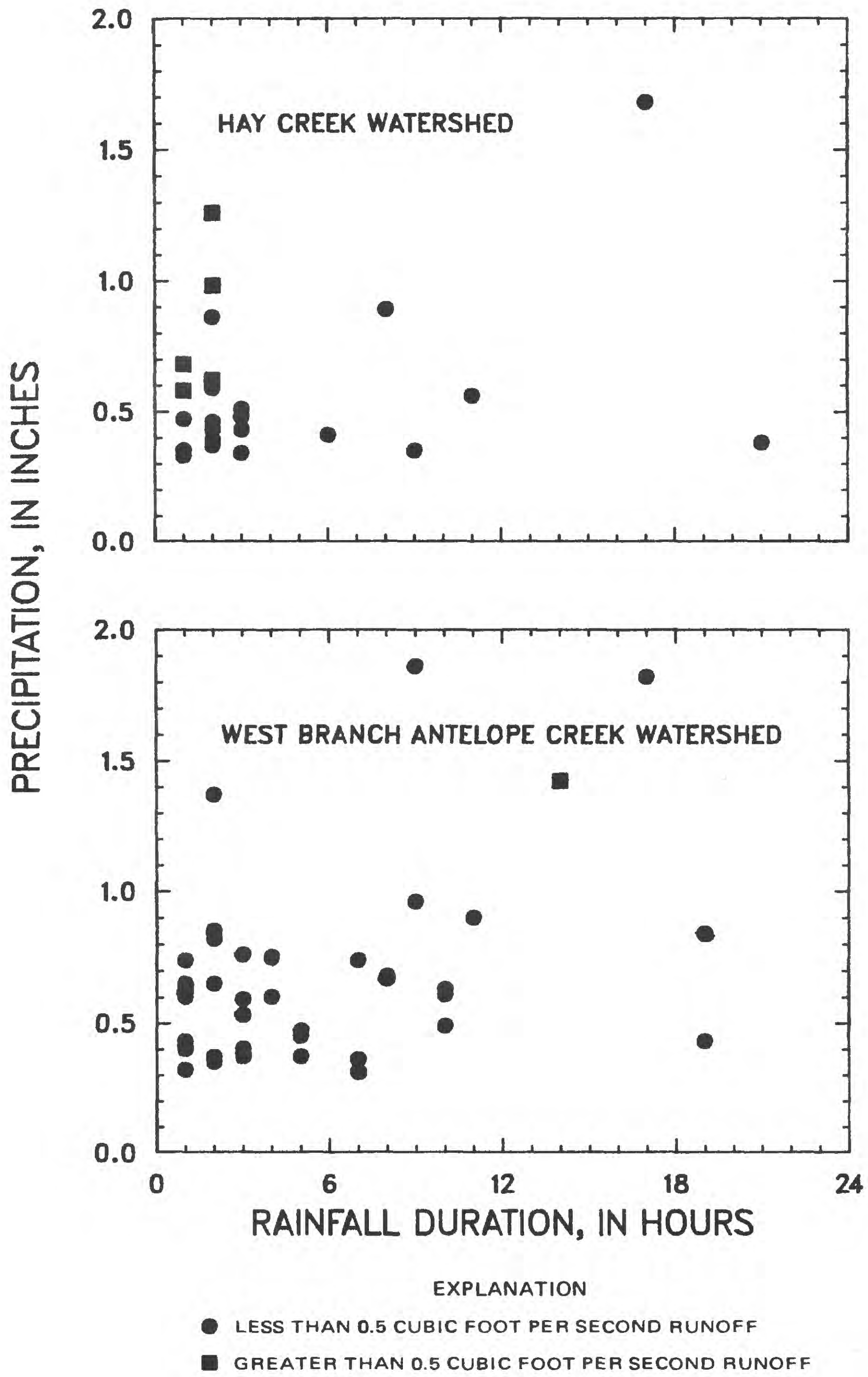


Figure 8.--Rainfall quantity versus duration for the Hay Creek and West Branch Antelope Creek watersheds.

However, if any flow was from interflow, the area of contribution probably was from the area directly adjacent to the stream. The ground-water flow had a minor but consistent contribution to the total runoff. This flow was discharged in the downstream 2 mi of the stream and, during periods of adequate moisture, contributed a couple of hundredths of a cubic foot per second to the stream. Channel flow had a great effect on the runoff. Channel-storage levels and vegetation-cover conditions for the antecedent period and the channel slope and geometry for the period probably were similar for the two rainstorms. Because these two storms were relatively small, overbank storage was not a factor in determining runoff.

Much of the runoff for the two storms was controlled by reservoir storage. Three stock-dam type reservoirs are on the main stem of Hay Creek. For the June 29 storm, these reservoirs were not full. In the case of the upstream reservoir located at stream-gaging station 06336510 (fig. 2), most of the runoff for the June 29 storm filled the reservoir. For the July 4 storm, the reservoirs were near capacity; therefore, they had a much smaller effect on the routing of the runoff.

The Beulah Trench study (U.S. Department of the Interior, 1977, p. 47-55) had sites adjacent to the West Branch Antelope Creek watershed. Rainfall simulation using a sprinkler system was used to determine hydrologic characteristics. One of the land classes, class A, that was used in the simulation corresponds to the downstream reaches of the West Branch Antelope Creek watershed. Class A consists of rolling uplands generally covered with a dense sod of native grasses and mainly used for livestock grazing. Land class A was used in the simulation at three different sites with two simulations at each site--one dry and one wet. The data from these simulations are given in table 4. The water-discharge and infiltration curves for each simulation are shown in figure 9.

Volumes of runoff that might be expected from selected storms were computed using infiltration rates obtained from the dry-condition rainfall simulations (U.S. Department of the Interior, 1977, p. 47-55). The rainstorms of different recurrence intervals and durations were obtained from the U.S. Weather Bureau (1961). Expected runoff, in inches, from storms of designated recurrence intervals, in years; duration, in minutes; magnitude, in inches; and antecedent moisture, in percent; are listed for each simulation site in table 5. For sites 2 and 4, with weighted mean slopes of 9.8 and 9.4 percent, more than 1.00 in. of rain in 60 minutes is needed to produce runoff. The greatest weighted mean slope is less than 9 percent when the basin is subdivided into 5-percent increments; therefore, even greater precipitation or intensity or both than shown in table 5 is required to produce the same quantity of runoff.

Snowmelt Runoff

Five spring snowmelt-runoff periods were recorded for the Hay Creek watershed and six for the West Branch Antelope Creek watershed. The discharge hydrographs for each station are shown in figure 10. The discharges of the snowmelt runoff are much larger than those of the rainfall runoff.

Table 4.-- *Data obtained from rainfall simulation at sites near West Branch Antelope Creek*

[U.S. Department of the Interior, 1977, p. 47-55]

Variable	Site					
	1 (Dry)	1 (Wet)	2 (Dry)	2 (Wet)	4 (Dry)	4 (Wet)
Date	9/21/76	9/21/76	9/17/76	9/18/76	9/23/76	9/24/76
Area (square feet)	2,510	2,510	2,290	2,290	2,662	2,662
Weighted mean slope (percent)	14.2	14.2	9.8	9.8	9.4	9.4
Aspect	East	East	West	West	South	South
Antecedent moisture (percent)	14.2	17.0	17.1	19.8	19.1	27.7
Clay (percent)	20.6	20.6	20.5	20.5	37.2	37.2
Root concentration (grams per 100 grams)	2.559	2.559	3.032	3.032	2.998	2.998
Bare soil and rock (percent)	1.3	1.3	2.3	2.3	5.0	5.0
Precipitation (inches)	1.39	1.69	1.61	1.83	1.64	1.73
Runoff (inches)	0.58	0.67	0.31	0.21	0.61	0.63
Sediment						
Pounds	5.92	13.08	3.00	1.58	5.11	7.99
Tons per square mile	32.9	72.6	18.3	9.6	26.8	41.8
Reconstructed runoff (inches)	0.67	0.55	0.22	0.04	0.49	0.45
Surface-soil bulk density (grams per cubic centimeter)	1.19	1.25	0.99	1.0	1.06	1.04

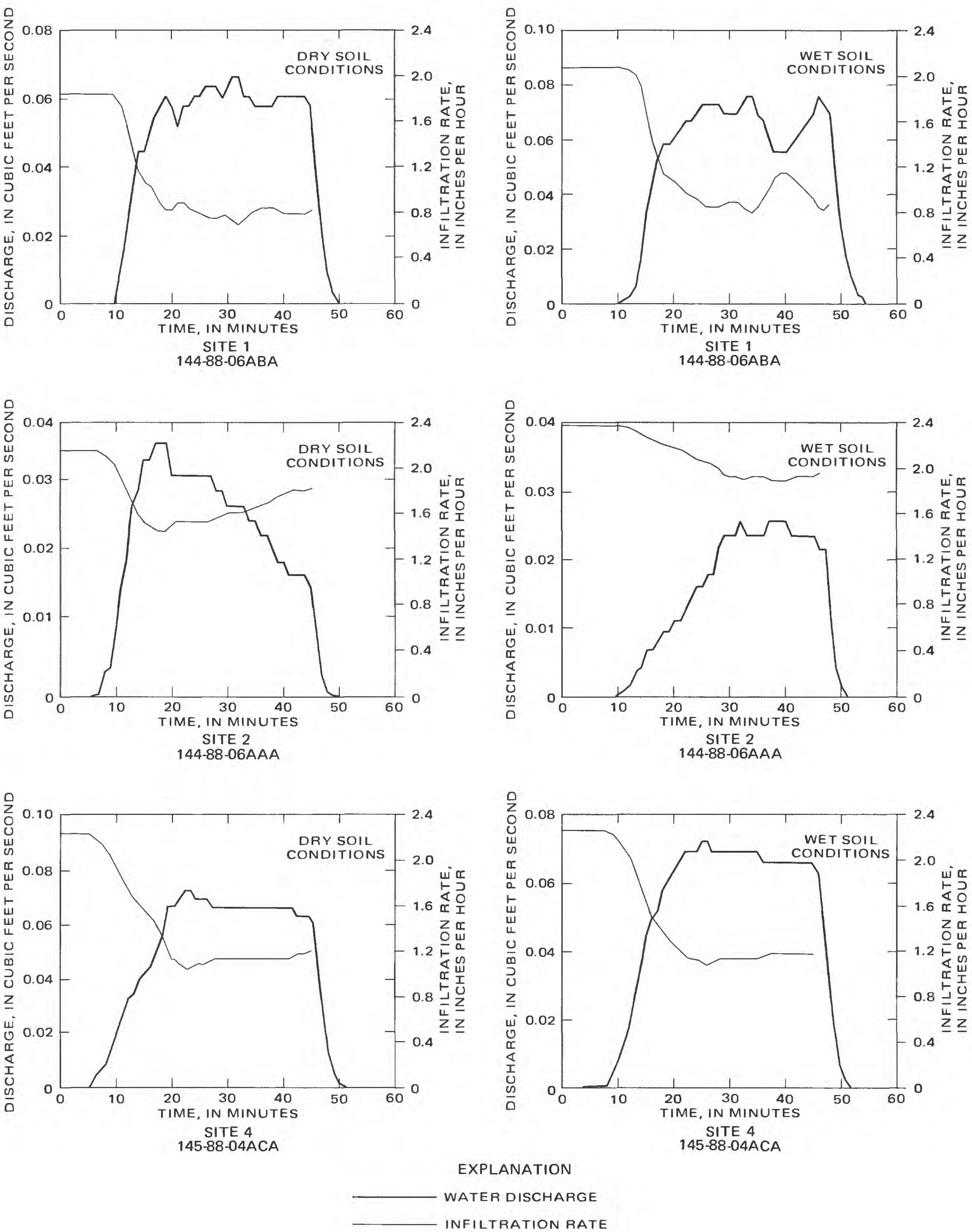


Figure 9.—Water-discharge and infiltration curves for rainfall-simulation sites near West Branch Antelope Creek. (Modified from U.S. Department of the Interior, 1977, p. 53).

Table 5.-- *Expected runoff using simulated data*

[U.S. Department of the Interior, 1977, p. 47-55]

Storm recurrence interval (years)	Rainfall duration (minutes)	Total rainfall magnitude (inches)	Runoff (inches)	
			Antecedent moisture 14.2 percent	Antecedent moisture 17.0 percent
		Site 1		
2	30	0.80	0.25	0.17
10	20	1.30	.66	.54
25	30	1.60	.94	.81
50	30	1.80	1.16	1.03
2	60	1.10	.21	.11
10	60	1.70	.71	.57
25	60	2.00	.97	.81
50	60	2.30	1.22	1.06
		Site 2		
2	30	0.80	0.02	0.00
10	30	1.30	.42	.00
25	30	1.60	.72	.52
50	30	1.80	.94	.74
2	60	1.10	.00	.00
10	60	1.70	.05	.00
25	60	2.00	.26	.05
50	60	2.30	.52	.27
		Site 4		
2	30	0.80	0.12	0.09
10	30	1.30	.55	.50
25	30	1.60	.89	.82
50	30	1.80	1.12	1.03
2	60	1.10	.00	.00
10	60	1.70	.41	.37
25	60	2.00	.68	.64
50	60	2.30	.96	.91

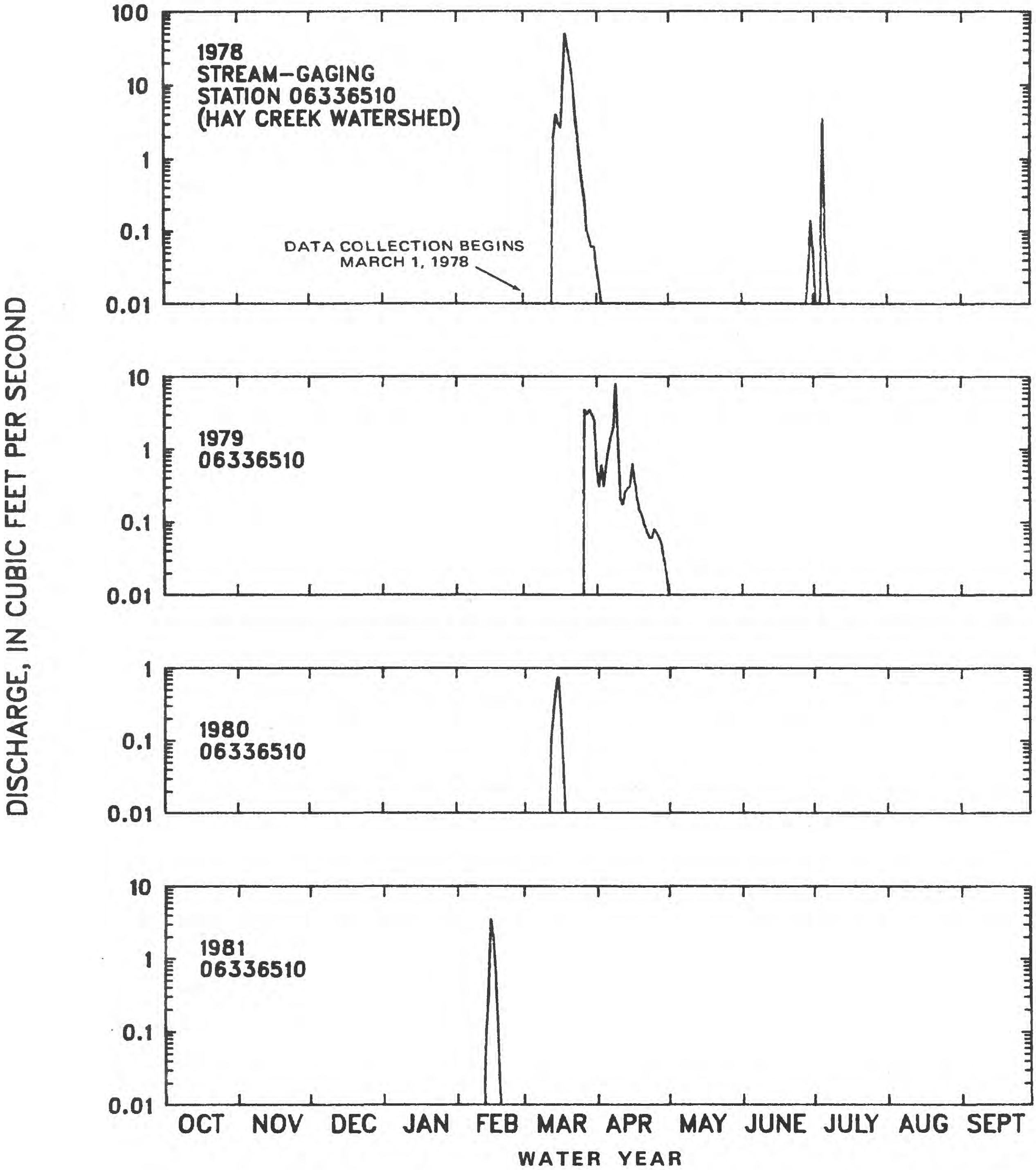


Figure 10.—Stream discharge for the period of record for stream-gaging stations in the Hay Creek and West Branch Antelope Creek watersheds.

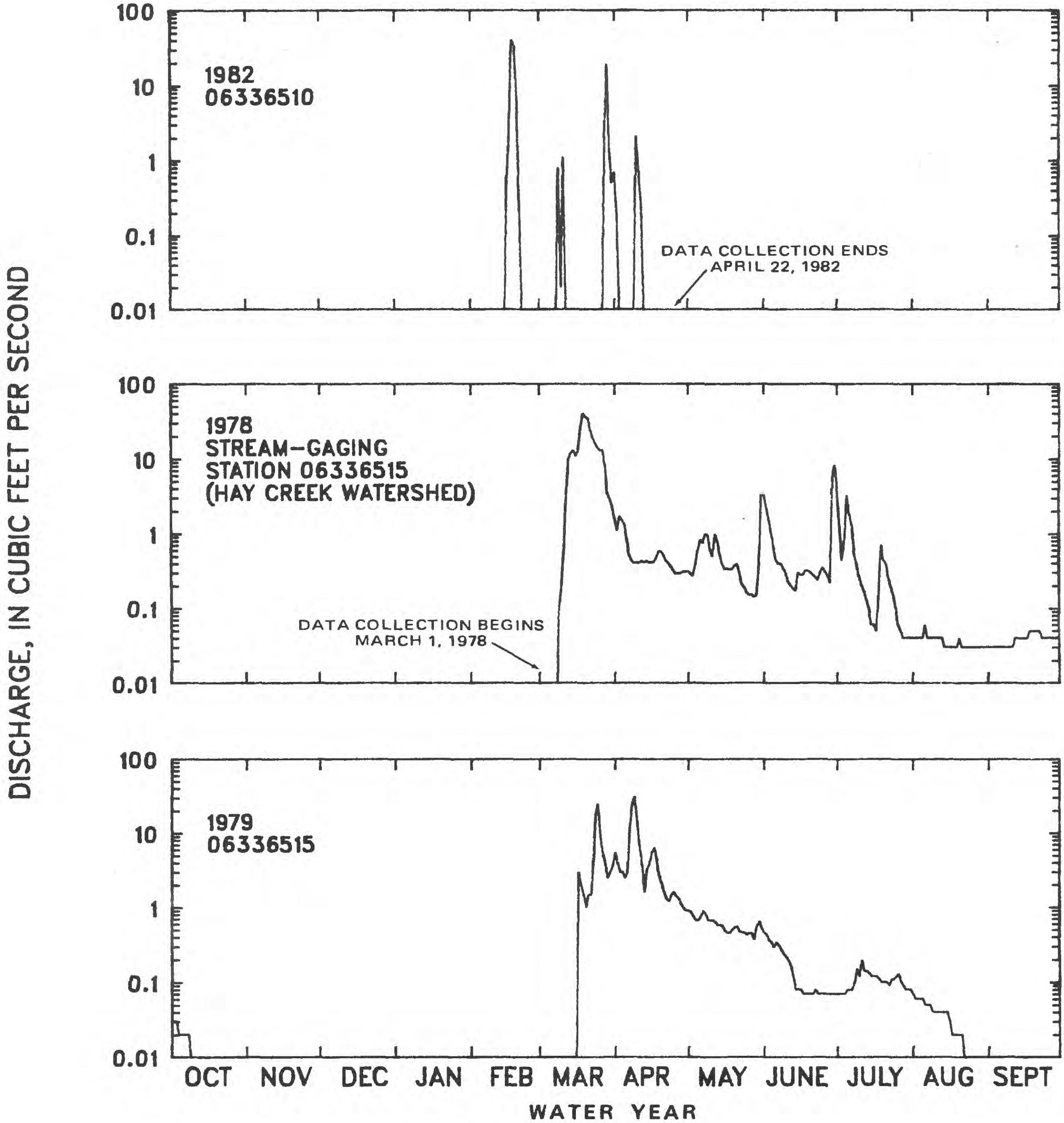


Figure 10.—Stream discharge for the period of record for stream-gaging stations in the Hay Creek and West Branch Antelope Creek watersheds--Continued.

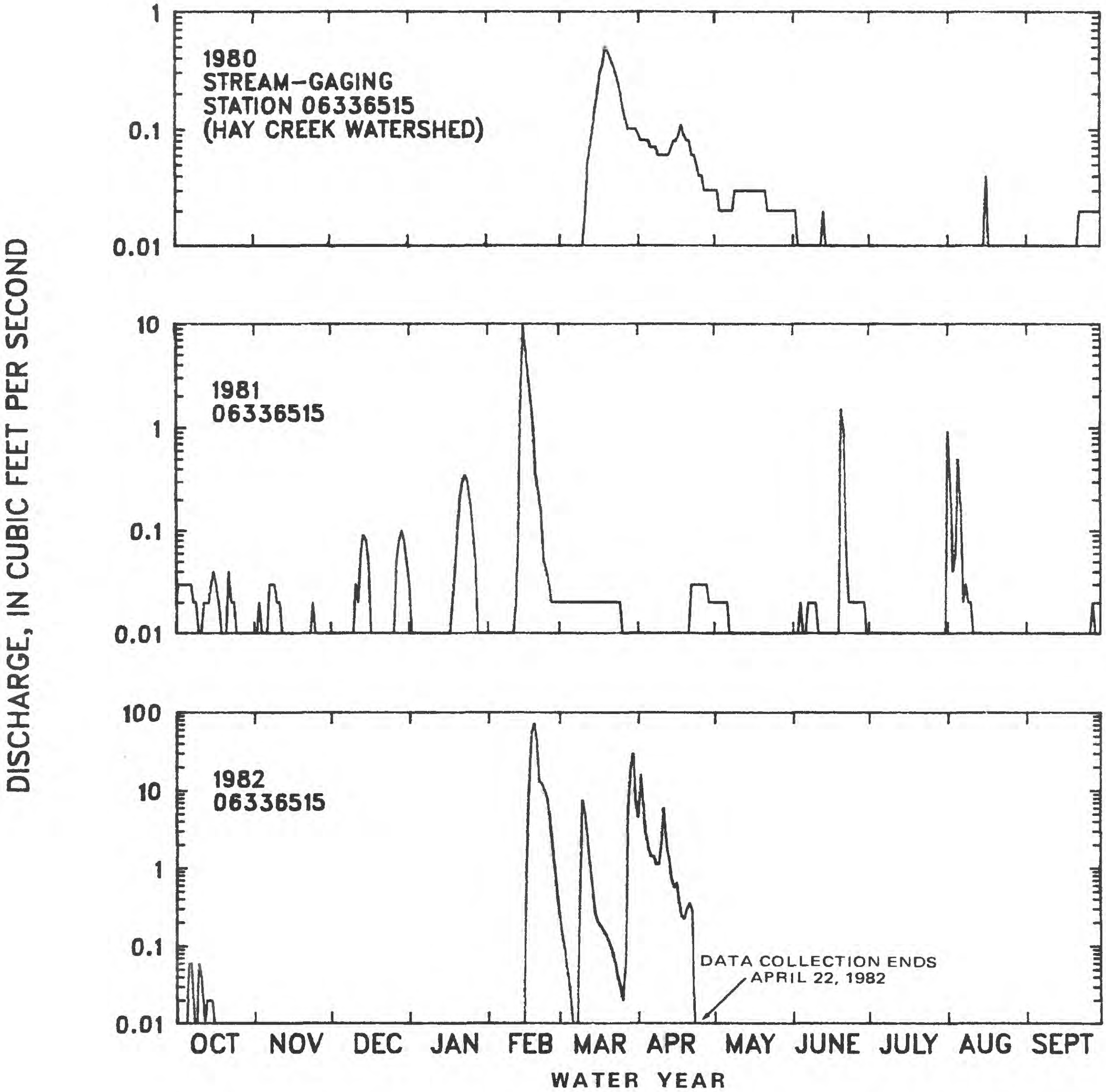


Figure 10.—Stream discharge for the period of record for stream-gaging stations in the Hay Creek and West Branch Antelope Creek watersheds--Continued.

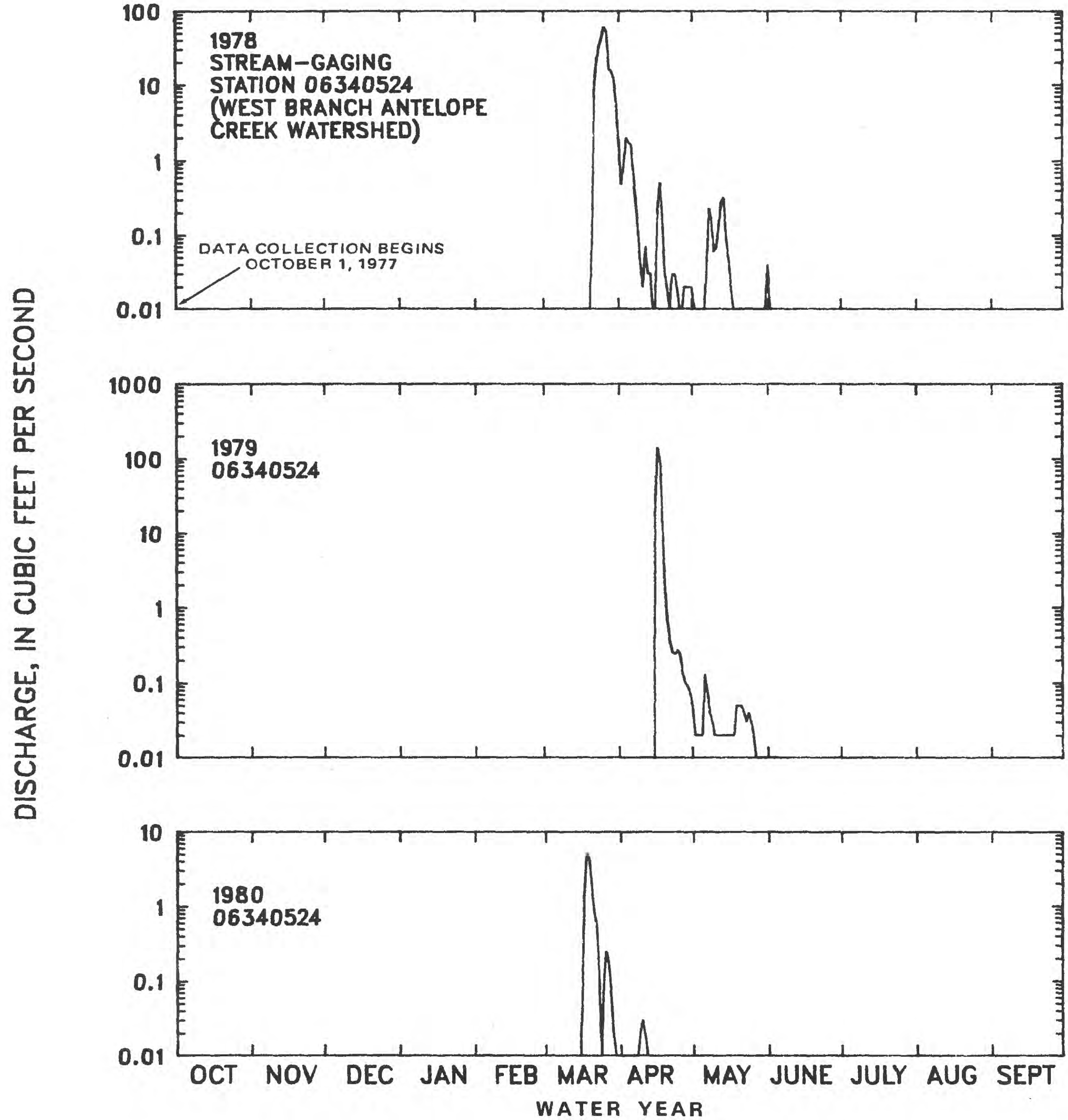


Figure 10.—Stream discharge for the period of record for stream-gaging stations in the Hay Creek and West Branch Antelope Creek watersheds--Continued.

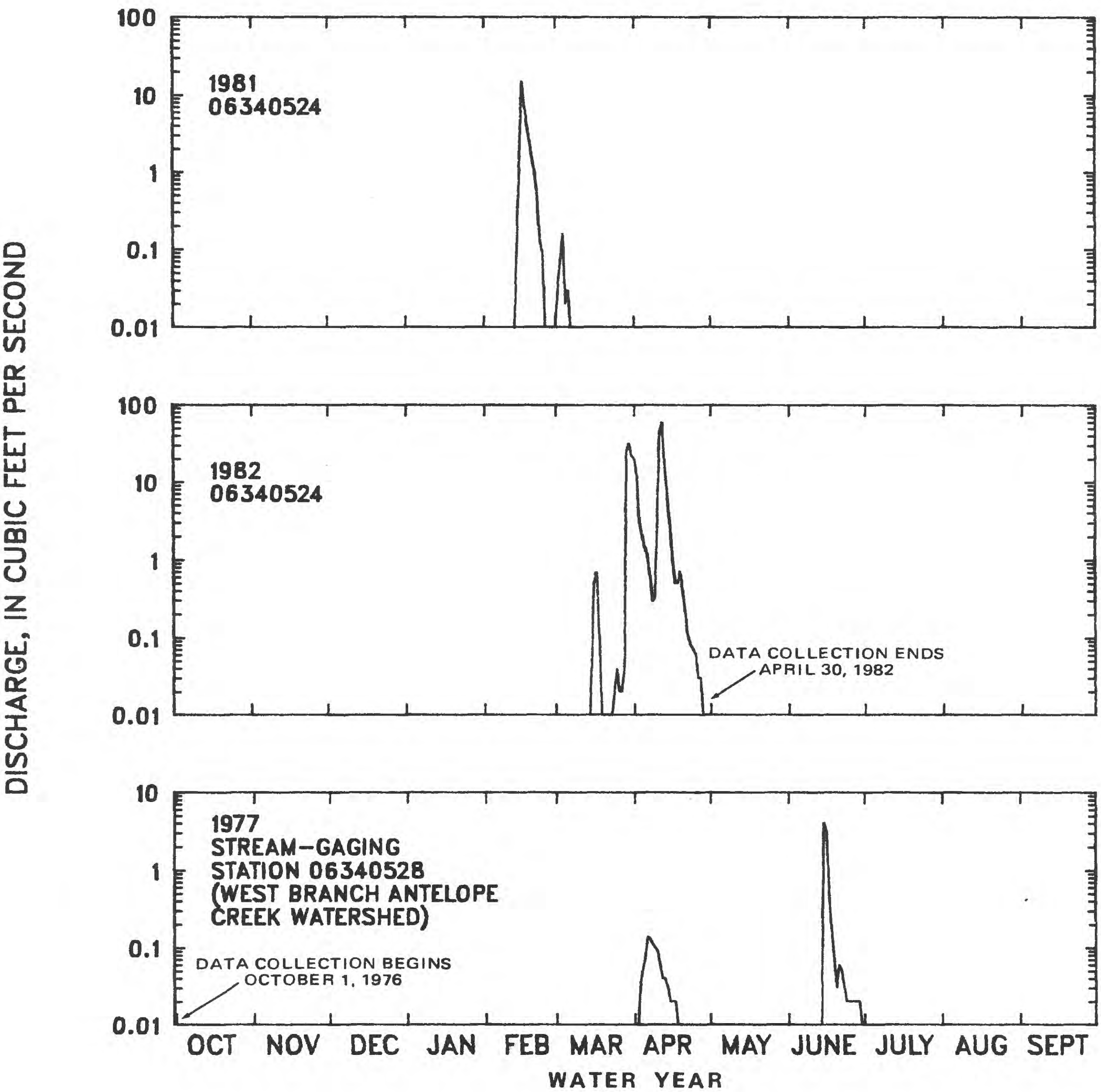


Figure 10.--Stream discharge for the period of record for stream-gaging stations in the Hay Creek and West Branch Antelope Creek watersheds--Continued.

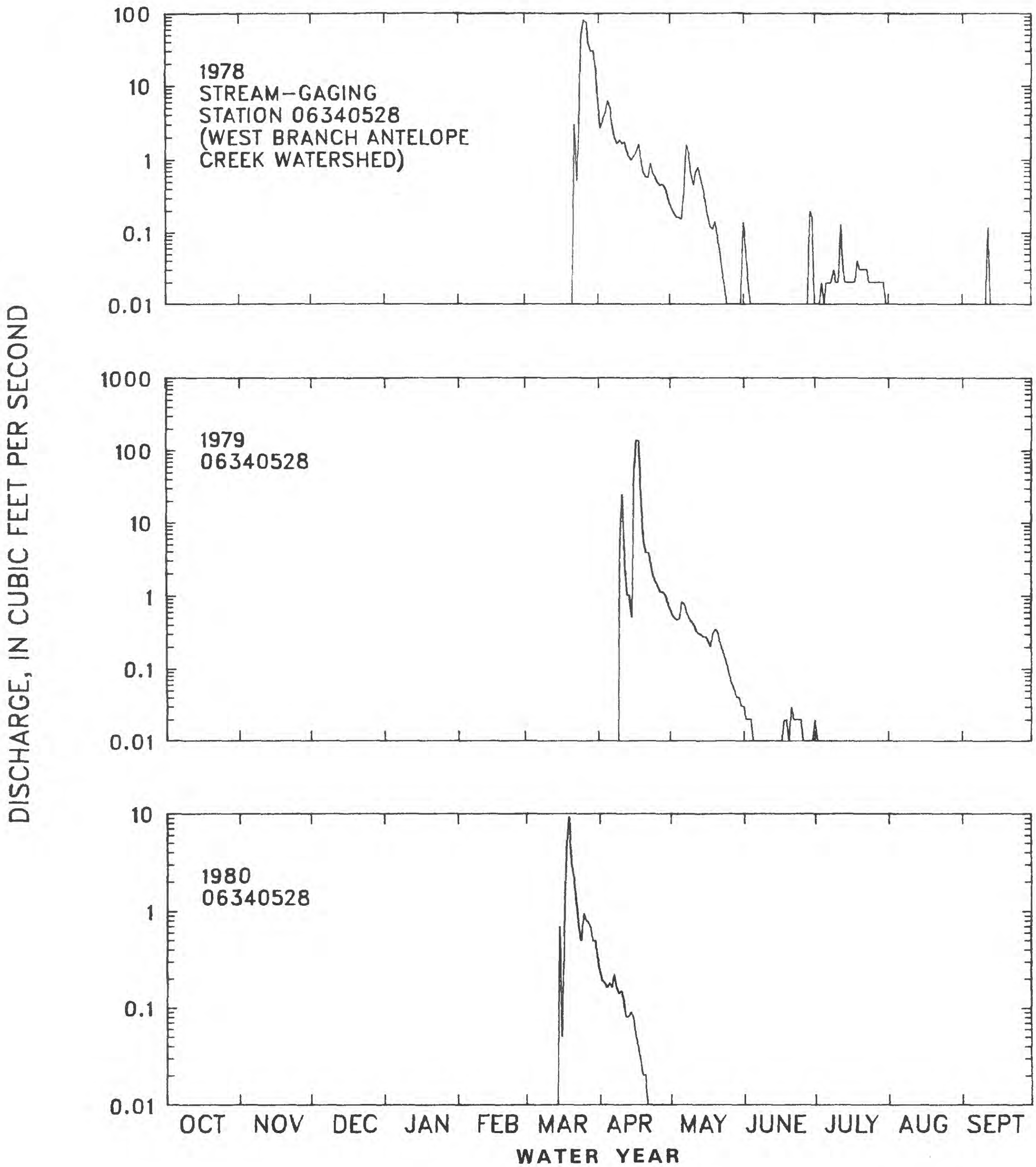


Figure 10.—Stream discharge for the period of record for stream-gaging stations in the Hay Creek and West Branch Antelope Creek watersheds--Continued.

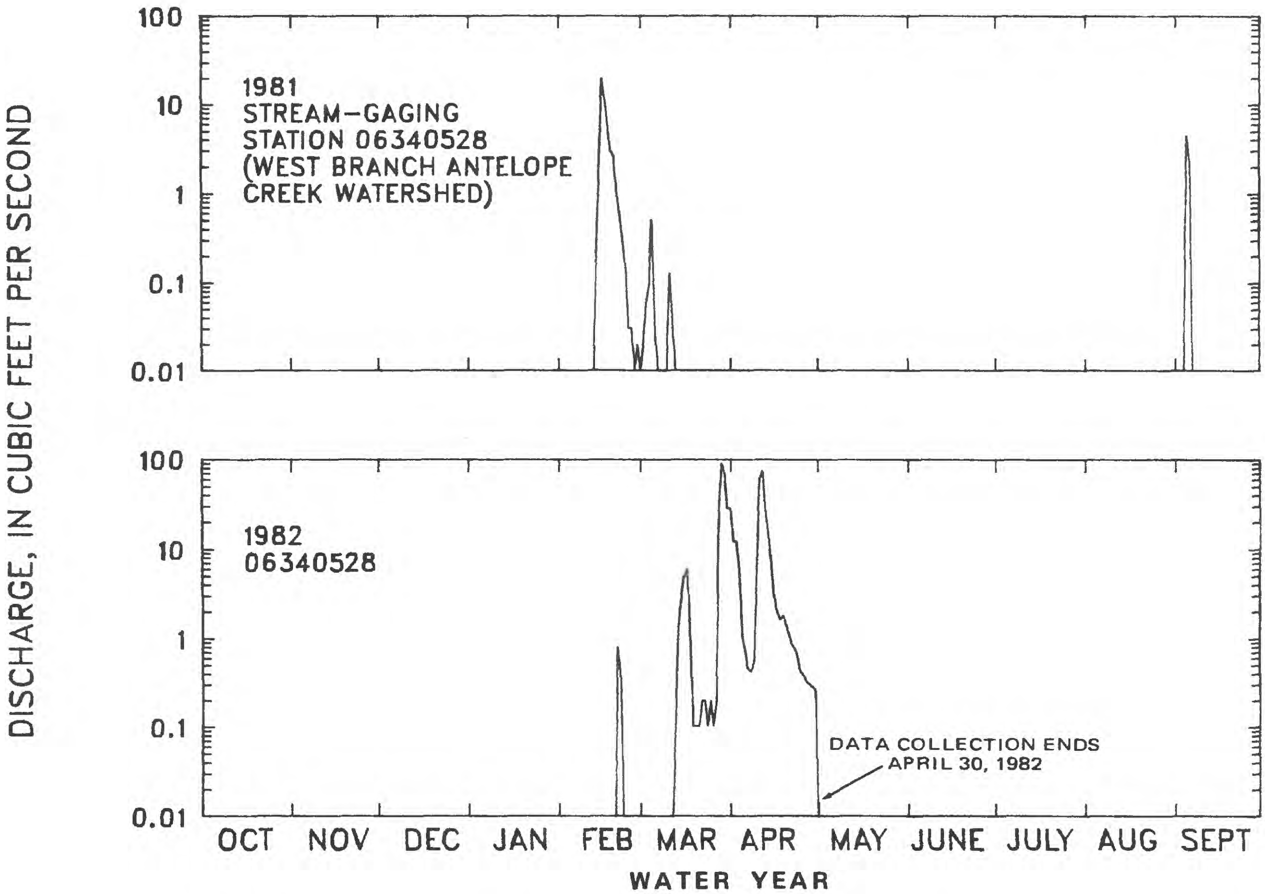


Figure 10.—Stream discharge for the period of record for stream-gaging stations in the Hay Creek and West Branch Antelope Creek watersheds--Continued.

Factors affecting water availability.--The antecedent conditions of snow accumulation can vary from day to day and from one area to another. To eliminate or simplify some of the factors affecting the antecedent conditions, a percentage of the total quantity of precipitation that falls during the winter commonly is used as the quantity of snow available for melt. A snow-depth-index method also commonly is used. The snow-depth-index method uses a point location to obtain snow-depth or snow-density measurements or both. These data then are used to represent the snow cover for that area. Both methods usually have gross errors.

The best method for determining snow cover, though very time consuming, is to make a ground snow survey. The snow distribution of February 27, 1979, for the West Branch Antelope Creek watershed was determined by a ground snow survey (fig. 11) which was made using a method developed for the prairie environment (Steppuhn and Dyck, 1974, and Steppuhn, 1976). From the snow-distribution data, the mean water equivalent for the study basin was 3.56 in.

In comparison, the snow distribution using the total snowfall data and the isohyetal method of distribution is shown in figure 12. Using this method, the mean water equivalent was 2.81 in. Not only is the mean water equivalent significantly different, but the distribution is radically different.

The same type of error can be demonstrated with the use of a single depth reading. From the snow-survey data, snow depths ranged from 0 to 8.4 ft, which is a large range. In order for the snow-depth-index method to be effective, a measuring location representing the mean depth for the basin needs to be chosen. This location varies depending on the depth of snow accumulation. The snow-depth-index method has the potential of having large errors, partly because it assumes a constant water equivalent distribution. Despite these disadvantages, the snow-depth-index method provides an easy and quick method of determining water equivalent and snow distribution.

To adequately predict snowmelt runoff, an accurate measurement of the snow distribution available for melt is essential but not easily obtainable. A snow survey just prior to the melt can best determine the water available for the snowmelt period.

Most of the research on the factors influencing snowmelt (table 1) has been done in mountainous or forested regions. The factors influencing snowmelt for these regions can be greatly different from the factors influencing snowmelt on a prairie. Extrapolating such analyses to the prairie environment requires some adjustments based on an understanding of the characteristics of snowmelt on the prairie. The energy-balance equation is used to determine the melt rate for the watersheds. A detailed discussion of the energy-balance equation and its use on the prairie is given in the "Supplemental Information" section.

Factors affecting water excess.--The two most significant factors affecting infiltration rates during snowmelt are soil moisture and temperature. Both have values that are continually changing. The soil-temperature profiles at the West Branch Antelope Creek weather station

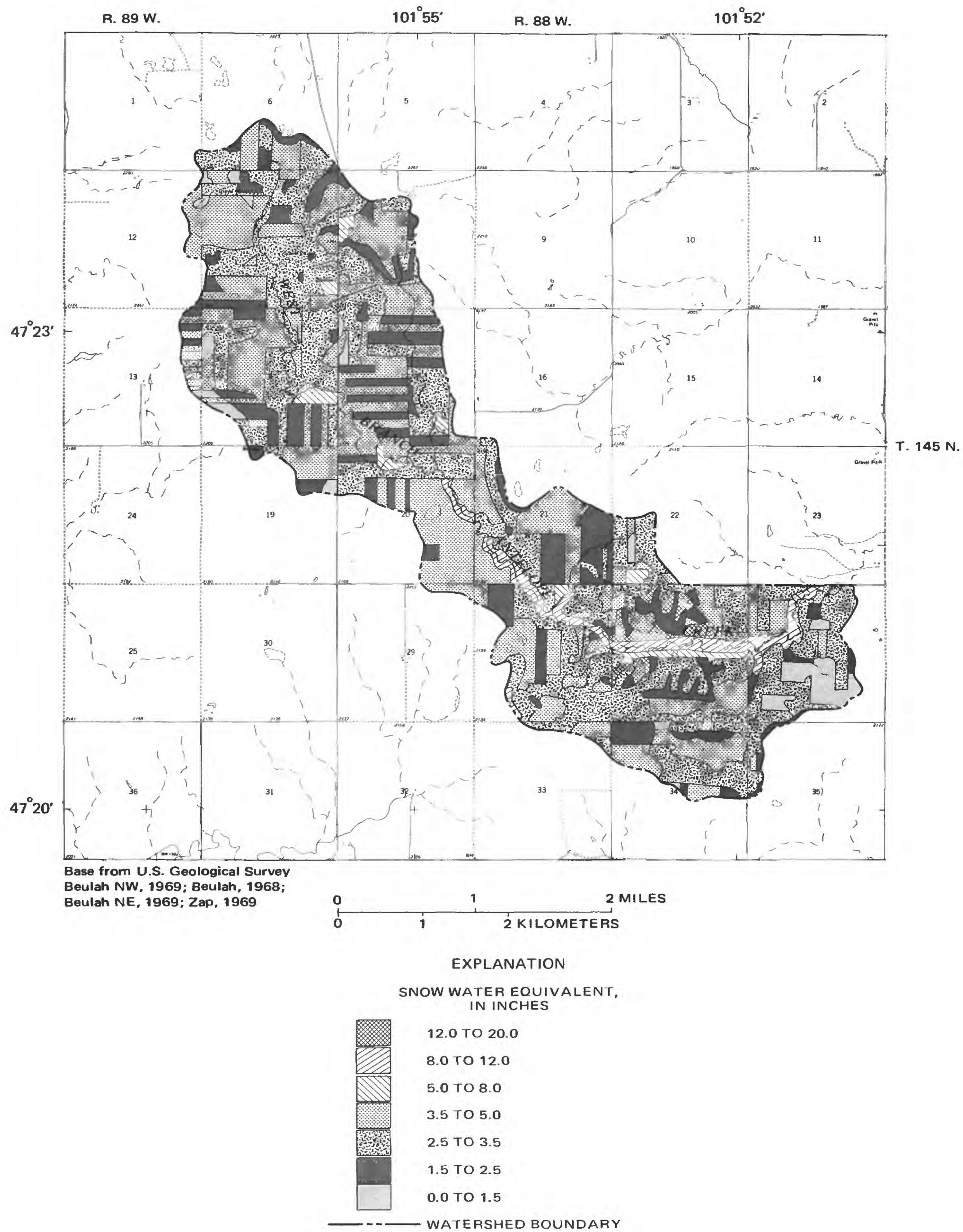


Figure 11.—Snow water equivalent distribution determined by ground survey in the West Branch Antelope Creek watershed on February 27, 1979.

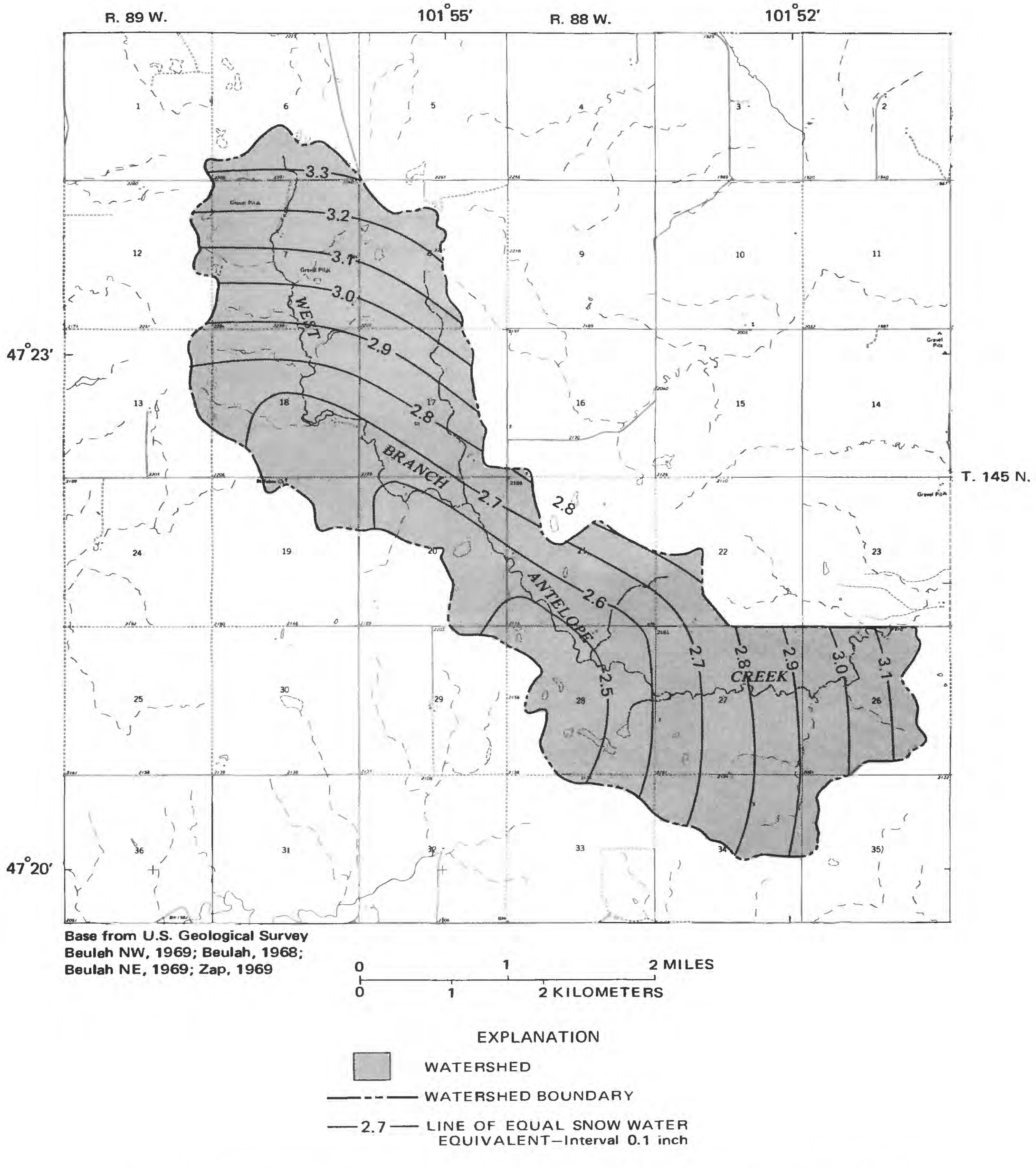


Figure 12.—Snow water equivalent distribution determined by total snowfall in the West Branch Antelope Creek watershed on February 27, 1979.

(station BD-7) are located in a grassland area where snow accumulates in a snowdrift. The temperature profiles for the 1979-80, 1980-81, and 1981-82 winters are shown in figure 13. Each year when runoff started at the stream-gaging station (station 06340528), the ground was frozen, and, during the instantaneous peak, the soil was still frozen at a depth of 0.4 ft.

In one extreme, a deep snowpack insulates the ground causing the soil not to freeze as deep and also causing the top layer of soil to thaw the slowest. In the other extreme, a fallow field with little or no snow cover would freeze deeper but the top layer of soil would thaw before lower layers. No data were collected in fallow fields.

By knowing the soil-moisture content before the snowmelt period and the soil temperature during the snowmelt period, gross infiltration rates can be predicted for the melt period. The variation of infiltration rates throughout the watershed and during the melt period is not known. North Dakota snow cover is patchy with the edge of these snow patches melting the fastest and changing the frozen condition of the soil. The effect of varying conditions of frozen soil and snow cover on the runoff process is not known.

Many snowmelt-runoff analyses treat evapotranspiration, depressional storages, and interception as insignificant or zero. These assumptions need to be verified. Treating interception as zero may be a justified assumption for the Fort Union coal region, but treating evapotranspiration and depressional storages as zero may not be a valid assumption. Granger and Male (1978) determined that evaporation accounted for 14 to 22 percent of the incoming energy to the snow surface in an open area during melt. Although little research has been done, potential effects of depressional storages appear to be significant enough not to be ignored.

Factors affecting water routing.--The commonly used runoff models have very simplified routing procedures, if any at all. Most routing procedures have been developed and designed for rainfall runoff. These routing procedures may be adequate depending on the particular routing procedure and required results. To adequately predict changes in snowmelt runoff due to mining activities, a minimum of routing runoff from small parts of the basin and routing flow through the channel is needed.

To the author's knowledge, there has been no research on the overland-flow routing of snowmelt runoff for a prairie environment. How critical overland-flow routing is in determining high flows is not known. Research in this area is needed.

Because ground-water flow is a very small part of high flow and most watersheds in the Fort Union coal region have ephemeral streams, a simple simulation of the ground-water flow system should adequately describe the ground-water flow processes.

Interflow is not well understood. For the prairie of North Dakota coal fields, interflow from rainfall runoff and snowmelt runoff is assumed to be very small. For moist frozen soils, the hydraulic conductivity, like infiltration, is two orders of magnitude less than for dry, unfrozen soils,

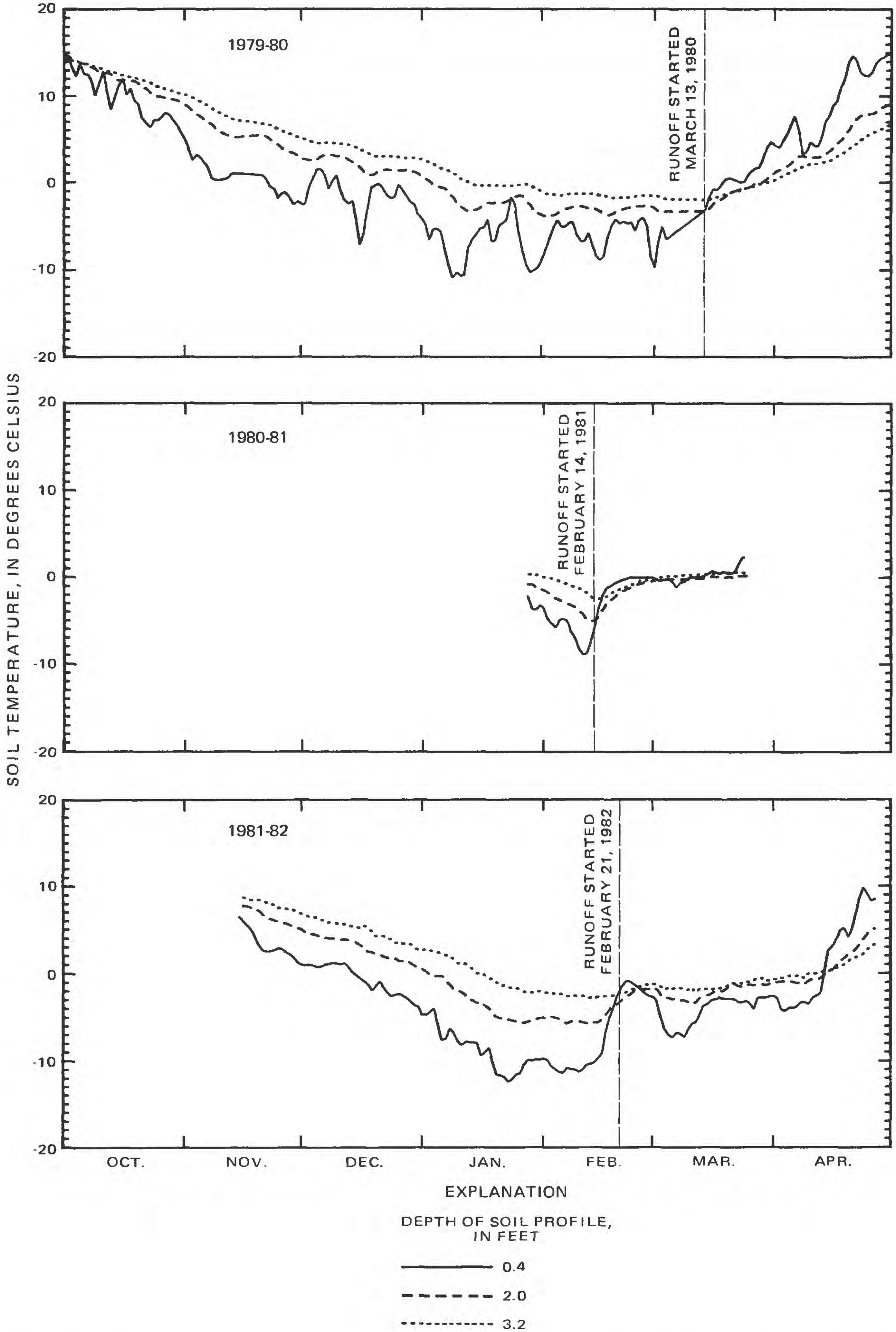


Figure 13.—Soil-temperature profiles at the West Branch Antelope Creek weather station (station BD-7).

resulting in negligible interflow. For dry, frozen soils, the hydraulic conductivity, like infiltration, would have magnitudes similar to those for dry, unfrozen soils. Research is needed to verify these inferences.

Channel-flow routing developed for rainfall runoff and used directly for routing snowmelt can have serious errors because the conditions are different. For snowmelt runoff, the channels can be full of snow and ice. The runoff is a diurnal process with freezing during the night. Temporary storage can be developed by snowbanks and ice jams. The effect of snow and ice on channel flow is almost impossible to predict. With roads on most section lines, numerous temporary reservoirs at culverts are created on any stream. The storage behind these road embankments needs to be simulated in channel-flow routing.

LOW FLOW

Low flow may not be a critical period for quantitative watershed analysis. For first-order streams in the Fort Union coal region of Montana and North Dakota, low-flow analysis is not needed because most of the streams are ephemeral, including Hay Creek and West Branch Antelope Creek. Not having to evaluate low flow simplifies a watershed analysis.

If low-flow analysis is warranted, the controlling processes and the factors that affect them need to be understood (table 6). The major processes that affect low flow are the same as those for high flow--water availability, water excess, and water routing. If low flow is a critical period, then the processes and the factors that affect them, as listed in table 6, need to be evaluated.

EROSION

Erosion is the process of weathering and transporting soil. Agents of erosion include water, wind, ice, gravity, and man's activities. To adequately evaluate a watershed for erosion by water, the controlling processes and the factors that affect them need to be understood. These processes and factors affecting the processes are numerous and complex (table 7). The major processes that affect erosion are sediment availability, sediment detachment, and sediment transport. The sediment-availability processes make sediment available for transport. The sediment-detachment processes determine the quantity of sediment from that which is available to that which is detached and can be transported. Sediment-transport processes determine the sediment load, which is comprised of the bed material and suspended load. A brief review of these processes and the factors that affect them is given in the following sections.

Sediment Availability

The two major controlling processes of sediment availability are natural existence and dustfall. The natural existence is governed by geologic processes; thus, for each area the available sediment can have different

Table 6.-- *Hydrologic processes that control low flow and factors affecting the processes*

Hydrologic processes	Factors affecting the processes
	Water availability

Ground-water storage........................	Storage capacity
	Recent recharge
	  Infiltration resulting from snowmelt
	  Infiltration resulting from rainfall
	  Bank storage resulting from high flow

Reservoir storage............................	Storage capacity
	Recent runoff
	  Snowfall
	  Rainfall
	  Base flow

Depressional storage........................	Storage capacity
	Recent runoff
	  Snowmelt
	  Rainfall

Interflow storage............................	Storage capacity
	Recent recharge
	  Infiltration resulting from snowmelt
	  Infiltration resulting from rainfall

	Water excess

Ground-water withdrawals....................	Water needs
	  Domestic
	  Agricultural

Evapotranspiration..........................	Vegetation conditions Wind velocity Air temperature Water temperature

Table 6.-- *Hydrologic processes that control low flow and factors affecting the processes*--Continued

Hydrologic processes	Factors affecting the processes
Water excess, Continued	
Reservoir withdrawals	Water needs Domestic Agricultural
Water routing	
Depressional-storage release	Drainage Hydrologic connection of moisture excess/ground water/interflow
Ground-water flow	Hydrologic connection of moisture excess/ground water/drainage channel
Interflow	Hydrologic connection of moisture excess/interflow conduits/ drainage channels
Channel flow	Antecedent Channel-storage levels Channel-vegetation conditions Runoff period Channel slope Channel geometry Backwater
Reservoir-storage releases	Operating schedule

Table 7.-- *Hydrologic processes that control erosion by water and factors affecting the processes*

Hydrologic processes	Factors affecting the processes
Sediment availability	
Natural existence	Recent geologic history
Dustfall	Wind
	Land use
	Soil moisture
	Soil type
	Human activity
	Mining
	Agriculture
	Construction
	Urbanization
Sediment detachment	
Raindrop impact	Antecedent
	Vegetation
	Soil moisture
	Soil erodibility
	Erosion period
	Rainfall intensity
	Rainfall-drop size
	Storm duration
	Air temperature
	Season of the year
Overland flow	Antecedent
	Basin slope and length
	Vegetation
	Soil moisture
	Soil condition
	Extent to which soil is frozen
	Human activities
	Agriculture
	Grazing
	Construction
	Logging
	Mining
	Urbanization

Table 7.-- *Hydrologic processes that control erosion by water and factors affecting the processes*--Continued

Hydrologic processes	Factors affecting the processes
Sediment detachment, Continued	
Overland flow, Continued......................	Erosion period
	Rainfall areal distribution
	Snowmelt rates
	Flow velocity and depth
	Slope and length
Mass wasting..................................	Topography
	Soil characteristics
	External loads
	Buildings
	Water
	Snow
	Excavation
	Undermining
	Tunneling
	Seepage erosion
	Shock
	Blasting
	Earthquake
Channel flow..................................	Antecedent
	Channel slope
	Channel geometry
	Bed and bank material characteristics
	Erosion period
	Flow depth
	Channel changes
	Deposition of sediment fines
Sediment transport	
Overland transport............................	Slope and slope length
	Flow depth
	Overland flow
	Depressional storage
	Particle-size distribution

Table 7.--*Hydrologic processes that control erosion by water and factors affecting the processes*--Continued

Hydrologic processes	Factors affecting the processes
Sediment transport, Continued	
Channel transport	Channel slope
	Flow depth
	Channel flow
	Overbank storage
	Reservoir storage
	Particle-size distribution
	Concentration of sediment fines

characteristics. The quantity of sediment that is available from dustfall is determined by the wind, land use, soil moisture, soil type, and human activity.

Sediment Detachment

The four major controlling processes of sediment detachment are raindrop impact, overland flow, mass wasting, and channel flow. By the very nature of erosion, classification of sediment detachment is arbitrary and relative. The impact of falling raindrops is the source of kinetic energy for detaching soil. Raindrop impact with little runoff is not likely to be an effective agent of erosion.

The force of overland-flowing water detaches material and makes it available for transport. Sheet, rill, and gully erosion are the results of overland flow. Sheet erosion is caused by removing the soil material by thin sheets of water. Rill erosion is caused by small concentrations of overland flow in rills and generally is considered to be evidence of more accelerated erosion than sheet erosion. Gullies generally are defined in size as large rills to ravines. Gully erosion is caused by concentration of runoff that results in large volumes of rapid velocity flow. However widespread overland flow may be, it is one of the most elusive processes to observe and measure. In fact, little is known of the general mechanics of sediment detachment by overland flow. Factors affecting sediment detachment by overland flow are listed in table 7.

The sediment-detachment process of mass wasting includes dry raveling, mudflows, and debris avalanches. All types of mass wasting provide direct or indirect sediment supply to the stream channels, thus disturbing ground surface, destroying vegetation, and altering prevailing drainage patterns.

The energy exerted by forces of channel flow detaches material making it available for transport. Streambank, streambed, and flood-plain scour are examples of sediment detachment by channel flow.

Sediment Transport

Transport of sediment is the process of conveying material entrapped by water (suspended load) and of moving channel-bed material (bed load). The two controlling processes of sediment transport are overland transport and channel transport. The factors affecting overland and channel transport are listed in table 7.

Sediment Analyses

Sediment availability of the two study basins is due to natural existence. On occasion, when large fields are left bare, winds are high, and soil is dry, significant dustfall may be important locally. Suspended sediment consists of only silt and clay, whereas bed material consists of 45 to 83 percent silt and clay (table 8).

Sediment detachment in the two study areas is caused mainly by overland flow. No mass wasting has been observed in either of the basins. With ephemeral streams, channel slopes of less than 35 ft/mi, and well-vegetated grass channels, sediment detachment by channel flow is minimal.

Erosion and transport of sediment by water in the Hay Creek and West Branch Antelope Creek watersheds are affected by the erodibility of the soil, which is controlled mainly by soil composition, structure, and vegetation cover. The soil associations in the two watersheds have been mapped and can be obtained from county soil reports (U.S. Department of Agriculture, 1958 and 1978). These reports include soil descriptions and area and slope data relative to each of the soil types that comprise a soil association.

The primary land use of the two study areas is agriculture. Each year, land-use data were collected in each watershed and are shown in figures 14 and 15. The only significant change in land use from year to year is the variation in the type of crop grown and in the acreage of land that is in summer fallow. The percentage of each land use has not changed significantly as noted in table 9. Farming practices can have a major effect on erosion. Detection of the impacts due to farming practices on basins the size of the Hay Creek or West Branch Antelope Creek watersheds or larger watersheds is very difficult because rainfall runoff occurs infrequently. Individual farming practices may change from year to year for a particular field making it difficult to detect individual effects from the net effect in the watershed.

Both overland and channel transport are important processes in the two watersheds. Because the particle size of suspended sediment is 0.062 mm or less (table 8), sediment is easily transported. However, each watershed has numerous section-line roads and stock-watering type reservoirs that can change sediment concentrations.

Table 8.-- *Suspended-sediment and bed-material size distribution in the Hay Creek and West Branch Antelope Creek watersheds*

	Hay Creek watershed			West Branch Antelope Creek watershed		
Station	06336510	06336515	06336515	06340524	06340528	06340528
Date	8/05/81	8/02/81	8/05/81	7/21/81	4/17/79	7/21/81
Sediment, suspended, fall diameter, percent finer than 0.004 millimeter	--	--	--	--	60	--
Sediment, suspended, fall diameter, percent finer than 0.016 millimeter	--	--	--	--	88	---
Sediment, suspended, fall diameter, percent finer than 0.062 millimeter	--	100	--	--	100	--
Bed material, sieve diameter, percent finer than 0.062 millimeter	83	--	52	73	--	45
Bed material, sieve diameter, percent finer than 0.125 millimeter	92	--	59	75	--	54
Bed material, sieve diameter, percent finer than 0.250 millimeter	96	--	67	81	--	69
Bed material, sieve diameter, percent finer than 0.500 millimeter	96	--	71	92	--	87
Bed material, sieve diameter, percent finer than 1.00 millimeter	98	--	77	94	--	91

Table 8.-- *Suspended-sediment and bed-material size distribution in the Hay Creek and West Branch Antelope Creek watersheds*--Continued

Station	Hay Creek watershed			West Branch Antelope Creek watershed		
	06336510	06336515	06336515	06340524	06340528	06340528
Bed material, sieve diameter, percent finer than 2.00 millimeter	98	--	87	96	--	94
Bed material, sieve diameter, percent finer than 4.00 millimeter	99	--	96	98	--	98

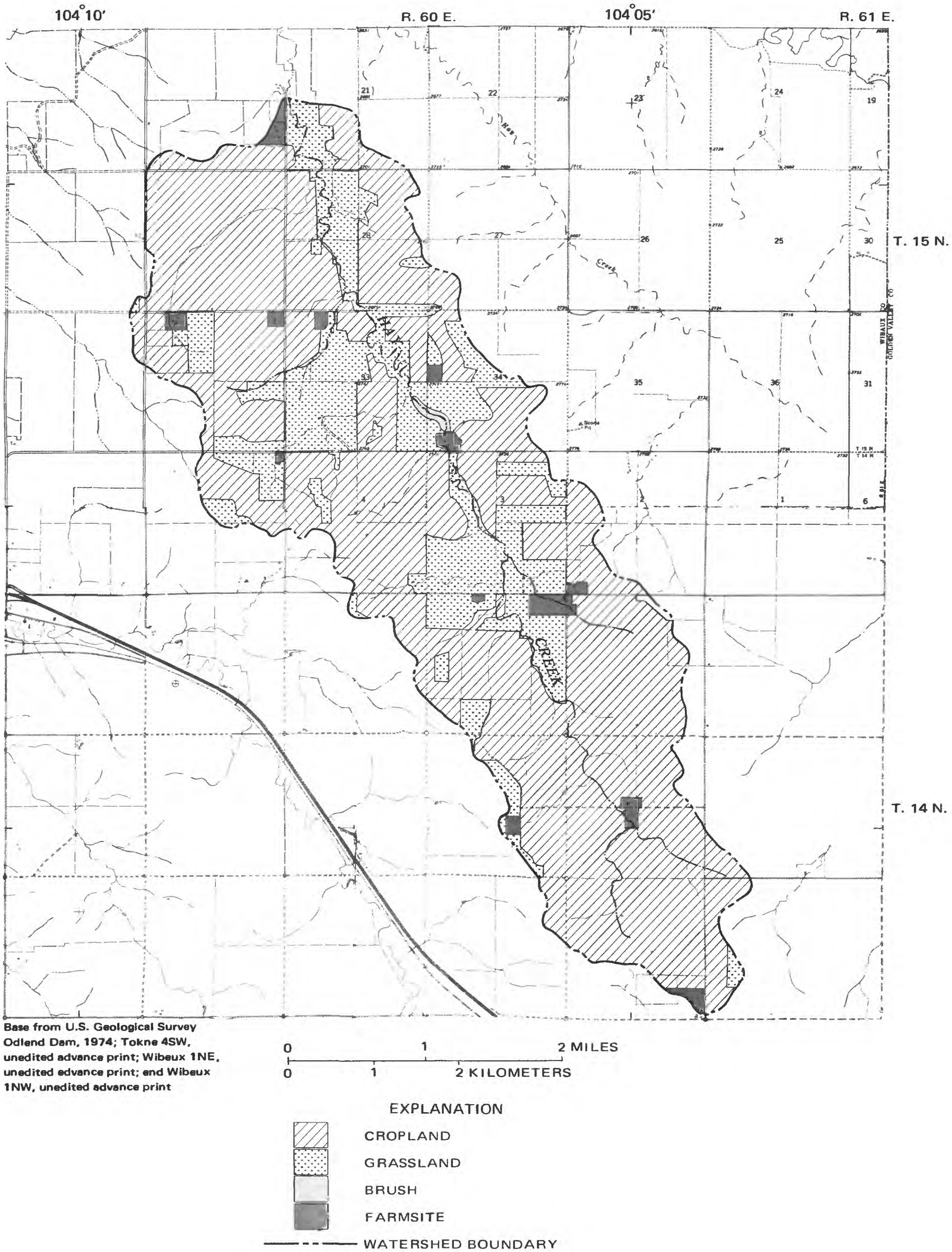


Figure 14.—Land use in the Hay Creek watershed, 1978-82.

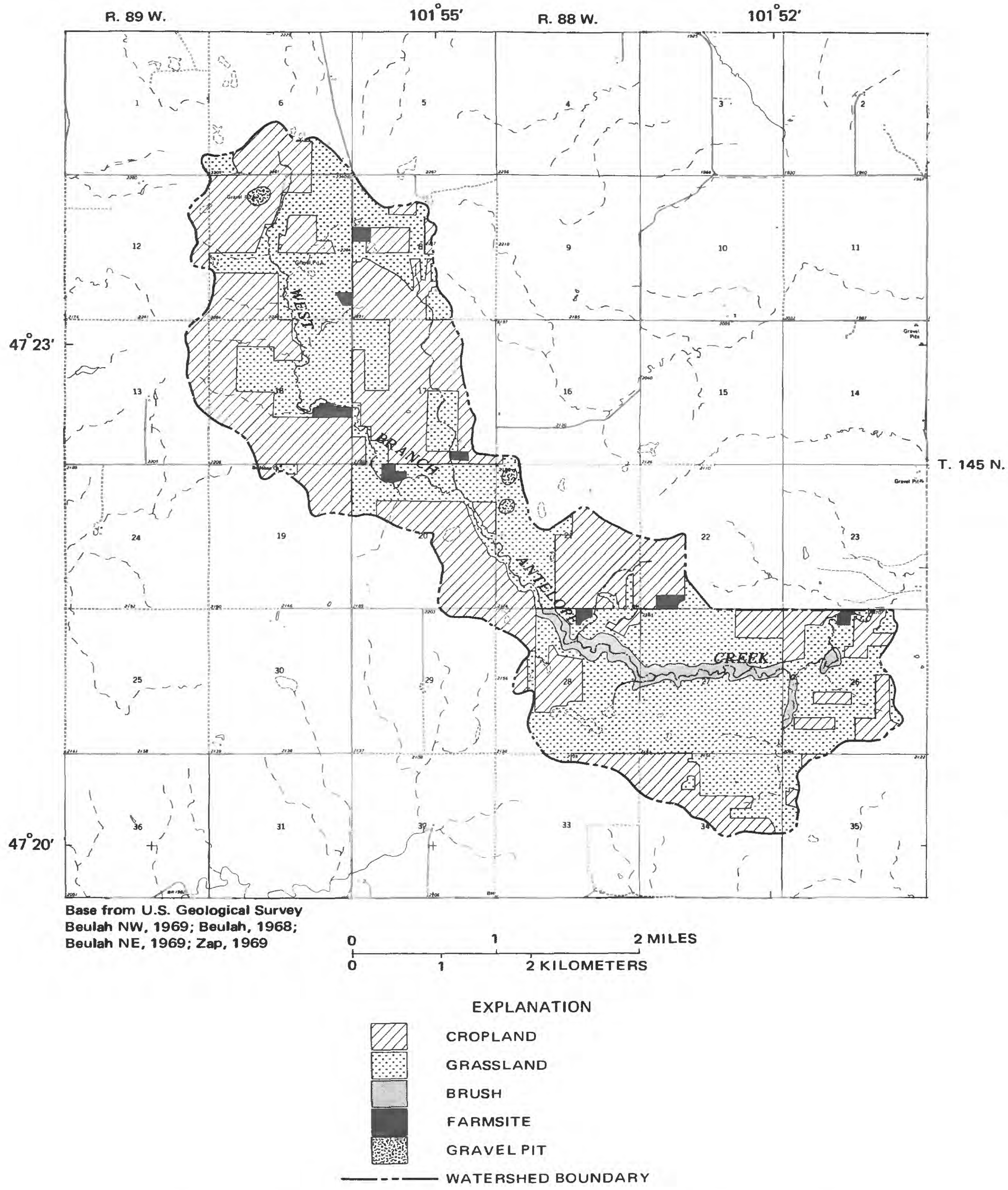


Figure 15.—Land use in the West Branch Antelope Creek watershed, 1978-82.

Table 9.-- *Land use in the Hay Creek and West Branch Antelope Creek watersheds*

Land use	Area (percent)						
	Winter 1978-79	Summer 1979	Winter 1979-80	Summer 1980	Winter 1980-81	Summer 1981	Winter 1981-82
	Hay Creek watershed (Total area, 11.41 square miles)						
Corn	0.0	0.4	0.0	0.2	0.0	0.3	--
Corn stubble	.0	.0	.4	.0	.0	.0	--
Fallow	35.3	34.4	34.5	35.9	40.6	24.8	--
Farm site	1.6	1.6	1.6	1.6	1.6	1.6	--
Grain	.0	36.6	.0	35.5	.0	48.8	--
Grain stubble	36.4	.0	36.5	.0	31.7	.0	--
Hayfield--pasture	26.7	27.0	27.0	26.8	26.1	24.5	--
	West Branch Antelope Creek watershed (Total area, 8.46 square miles)						
Brush	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Corn	.0	2.9	.0	2.5	.0	5.0	.0
Corn stubble	.1	.0	2.2	.0	.6	.0	5.0
Fallow	19.7	19.6	21.1	15.8	21.9	17.8	18.1
Farm site	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Grain	.0	23.2	.0	27.9	.0	21.9	.0
Grain stubble	25.6	.0	21.9	.0	24.9	.0	21.9
Gravel pit	.0	.0	.0	.2	.2	.2	.2
Hayfield--pasture	51.4	51.1	51.6	50.4	49.2	51.9	51.6

Summaries of suspended-sediment concentrations collected at the stream-gaging stations in the two watersheds are listed in table 10. Most of the sediment samples were collected from snowmelt runoff. The sediment concentrations are relatively small as would be expected for snowmelt runoff. Correlation between snowmelt-runoff sediment concentrations and various combinations of specific conductance, discharge, and water temperature was unsuccessful. For the station at the outlet of the Hay Creek watershed, station 06336515, suspended-sediment concentrations for snowmelt runoff ranged from 4 to 231 mg/L (milligrams per liter). For the station at the outlet of the West Branch Antelope Creek watershed, station 06340528, suspended-sediment concentrations for snowmelt runoff ranged from 9 to 325 mg/L.

Very little rainfall runoff occurred during the study period; consequently, few sediment samples were obtained. Sediment concentrations from rainfall runoff are expected to be much greater than those from snowmelt runoff although there is a lack of data from the two watersheds to verify the assumption. In the Beulah Trench study (U.S. Department of the Interior, 1977, p. 47-55), sediment concentrations were determined during the rainfall simulations. The runoff and sediment-concentration curves for each simulation are shown in figure 16. From these curves the maximum sediment concentration was about 2,350 mg/L. These curves show the variability of sediment concentrations of both dry and wet conditions.

CHEMICAL QUALITY

Processes

The chemical constituents in streams are derived from many different sources including soils and rocks, organic material, and atmosphere. The chemical processes that control solute concentrations include precipitation-dissolution reactions, redox reactions, ion-exchange reactions, and adsorption-desorption processes. The hydrologic processes and factors affecting the processes that control the chemical quality of streamflow are listed in table 11. Hem (1970, p. 3) stated "As the chemical composition of natural water is controlled by many interrelated processes, it follows that some understanding of these processes is needed before one can speak or act intelligently toward the aim of water-quality control and improvement." Hem (1970) and Velz (1970) provided an in-depth discussion of these processes.

Chemical-Quality Analyses

Chemical analyses of the water samples collected at each of the stream-gaging stations were presented by Emerson and others (1983). Statistical summaries of the water-quality data are listed in the "Supplemental Information" section. These summaries include values for the maximum, minimum, mean, and standard deviation, and values for the 95, 75, 50, 25, and 5 percentiles. For constituents with less than five measurements, only maximum and minimum values are given. Because the sampling schedule varied throughout the period of record, the list of water-quality variables used in the table and the number of measurements of an individual constituent may vary.

Table 10.-- *Summary of suspended-sediment concentrations in the Hay Creek and West Branch Antelope Creek watersheds*

Station	Number of samples	Descriptive statistics, Milligrams per liter: Maximum	Minimum	Mean	Standard deviation	Percent of samples in which concentrations, in milligrams per liter, were less than or equal to those shown: 95	75	50	25	5
				Hay Creek watershed						
06336510	15	2,580	22	257	647	2,580	151	48	35	22
06336515	37	596	4	78	138	491	54	30	12	6
				West Branch Antelope Creek watershed						
06340524	44	442	4	83	103	364	82	41	24	6
0634052	66	325	4	73	82	279	103	38	14	4

The Piper diagrams for Hay Creek indicate a relative downstream increase in magnesium and sulfate (fig. 17). For stream-gaging station 06336510, the dominant constituents are calcium, bicarbonate, and sulfate. Calcium never exceeded 66 percent of the cations. Bicarbonate never exceeded 90 percent of the anions and sulfate never exceeded 69 percent. For stream-gaging station 06336515, the dominant constituents are magnesium and sulfate. Magnesium never exceeded 54 percent of the cations and sulfate never exceeded 83 percent of the anions.

A computer program, WATEQF (Plummer and others, 1976), was used to model the thermodynamic speciation of inorganic ions and complex species in solution for each water analysis. The results of the evaluation are shown in figures 18 and 19. The dissolution of dolomite and gypsum between the upstream gaging station 06336510 and the downstream gaging station 06336515 along Hay Creek is indicated and explains the relative downstream increase in magnesium and sulfate. Saturation indices with respect to amorphous iron hydroxide, calcite, and quartz do not vary greatly with stream location. Because stream water always is oversaturated with respect to these minerals, processes involving solute exchange between these minerals and stream water probably are in stable equilibrium.

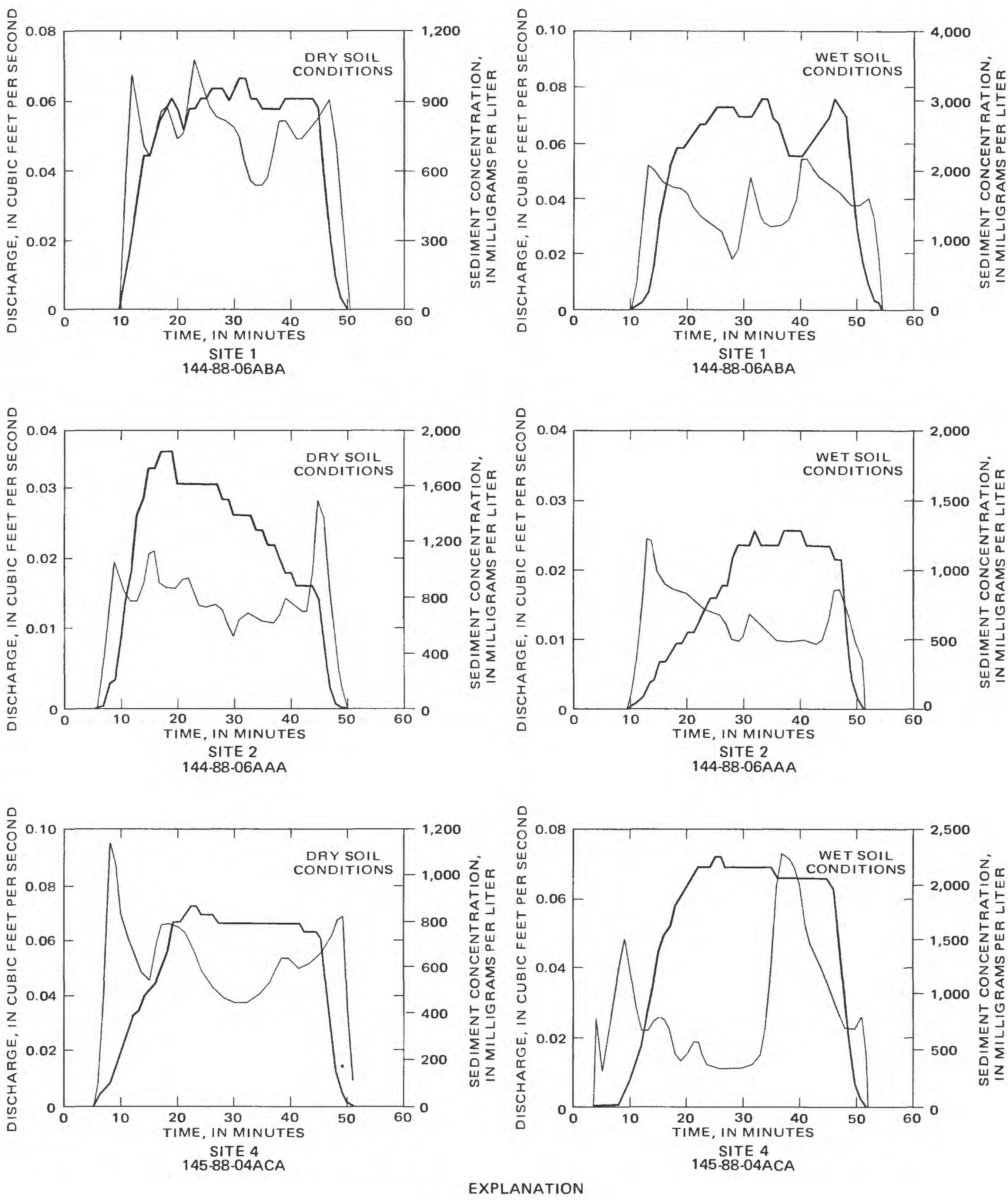


Figure 16.—Water-discharge and sediment-concentration curves for rainfall-simulation sites near West Branch Antelope Creek. (Modified from U.S. Department of the Interior, 1977, p. 53).

Table 11.-- *Hydrologic processes and factors affecting chemical quality of streamflow*

Hydrologic processes	Factors affecting the processes
Primary chemical source availability	

Soils and rocks	Geologic history
	Human activities
	  Urban development
	  Industrial- and energy-development waste
	  Animal waste
	  Tillage practices
	  Fertilizer loading

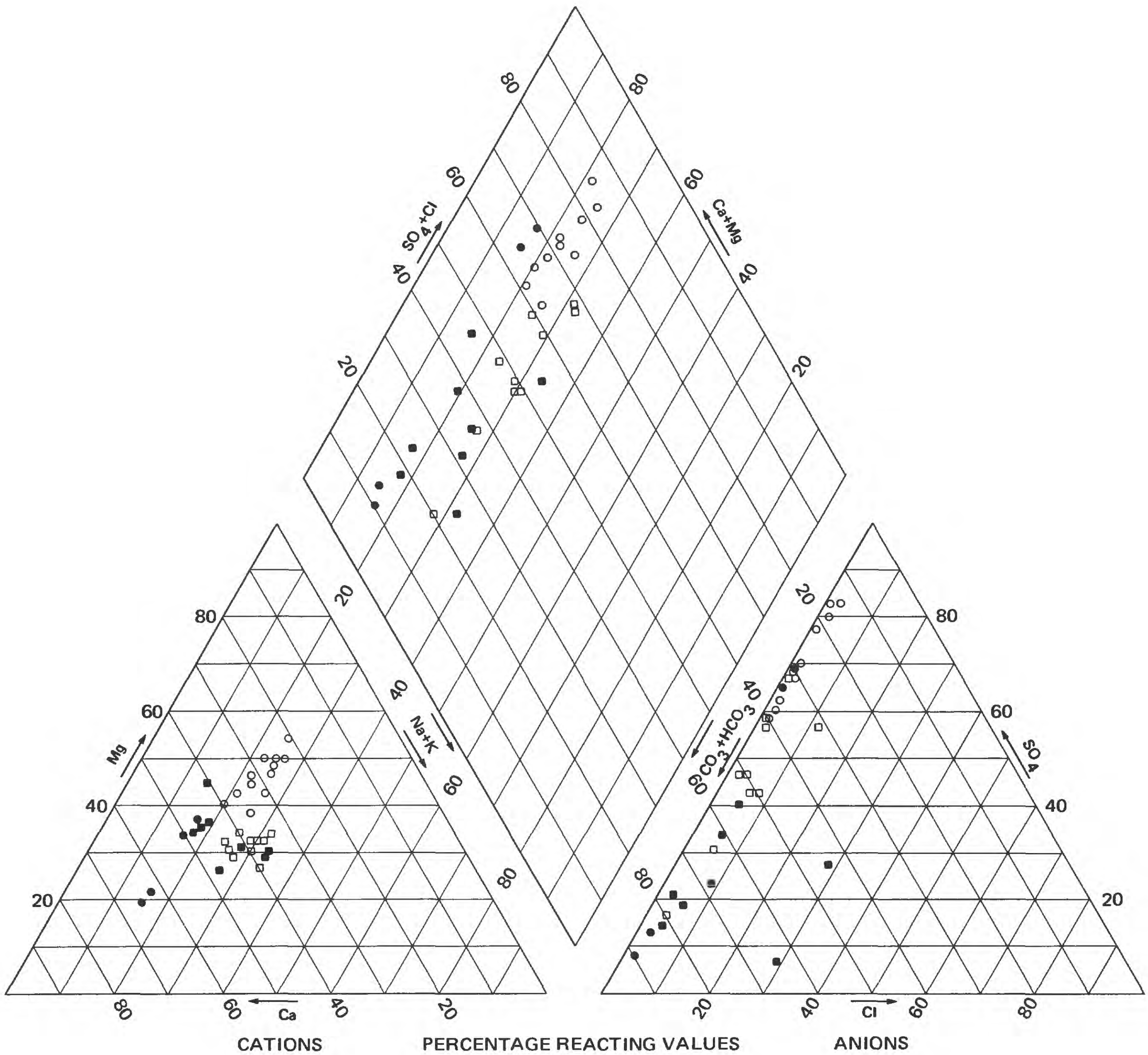
Organic material	Vegetation history
	Human activity
	  Urban development
	  Industrial- and energy-development waste
	  Animal waste
	  Tillage practices
	  Pesticide loading

Atmosphere	Climate
	Human activities
	  Industrial emission
	  Fossil-fuel combustion
	  Agricultural practices

Chemical activity	
Precipitation-dissolution reactions	Temperature pH Concentration and nature of constituents Contact time Biochemical activities Sediment characteristics

Table 11.-- *Hydrologic processes and factors affecting chemical quality of streamflow*--Continued

Hydrologic processes	Factors affecting the processes
Chemical activity, Continued	
Redox reactions	Temperature pH Redox potential Concentration and nature of constituents Contact time Biochemical activities Sediment characteristics
Ion-exchange reactions	Temperature pH Concentration and nature of constituents Contact time Biochemical activities Sediment characteristics
Adsorption processes	Temperature pH Concentration and nature of constituents Contact time Biochemical activities Sediment characteristics
Constituent transport	
Overland transport	Sediment transport Overland routing
Channel transport	Sediment transport Channel routing



EXPLANATION

- ● STREAM-GAGING STATION 06336510 (HAY CREEK WATERSHED)
- ○ STREAM-GAGING STATION 06336515 (HAY CREEK WATERSHED)
- ■ STREAM-GAGING STATION 06340524 (WEST BRANCH ANTELOPE CREEK WATERSHED)
- □ STREAM-GAGING STATION 06340528 (WEST BRANCH ANTELOPE CREEK WATERSHED)

Figure 17.—Major constituents in water at stream-gaging stations in the Hay Creek and West Branch Antelope Creek watersheds.

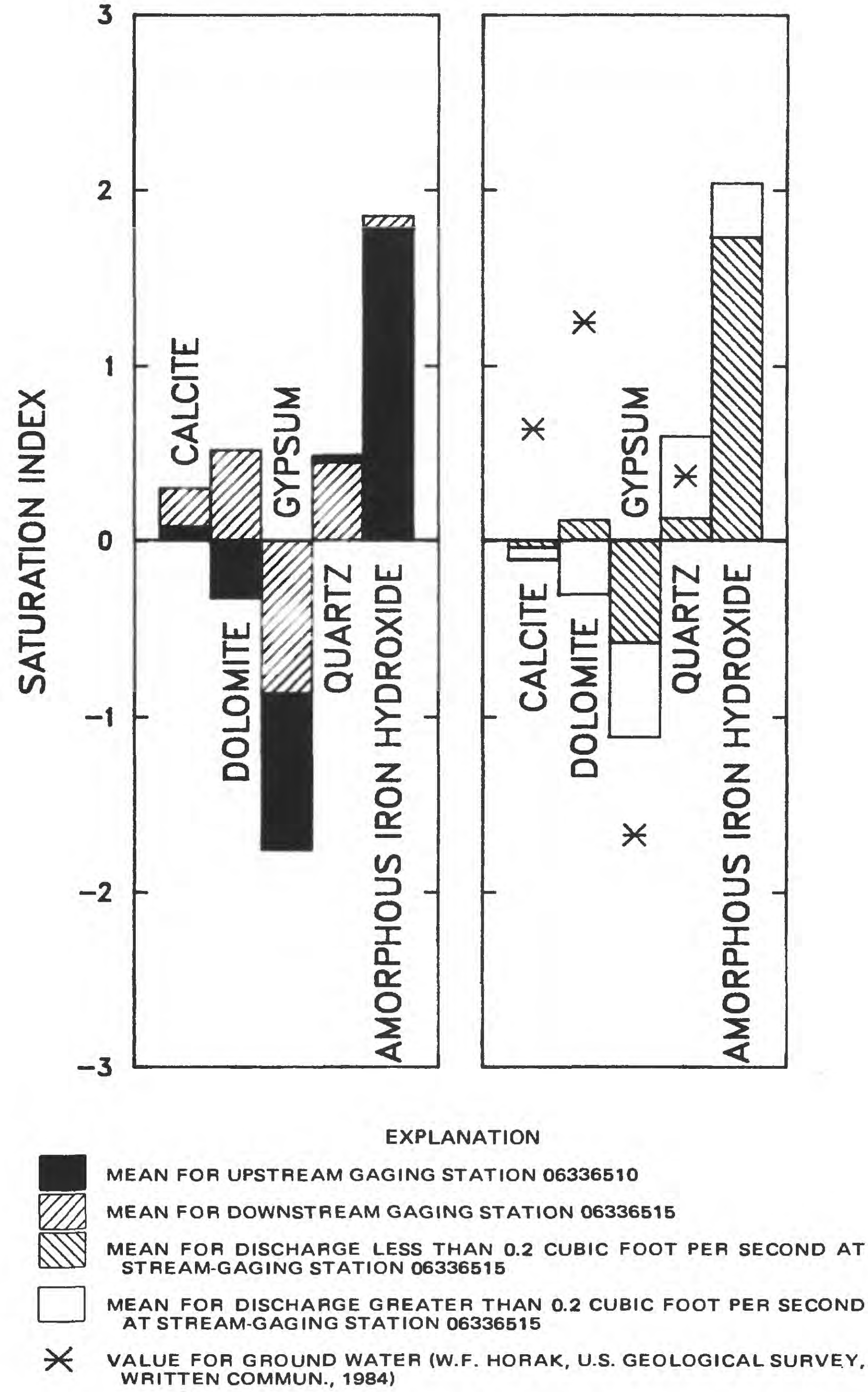
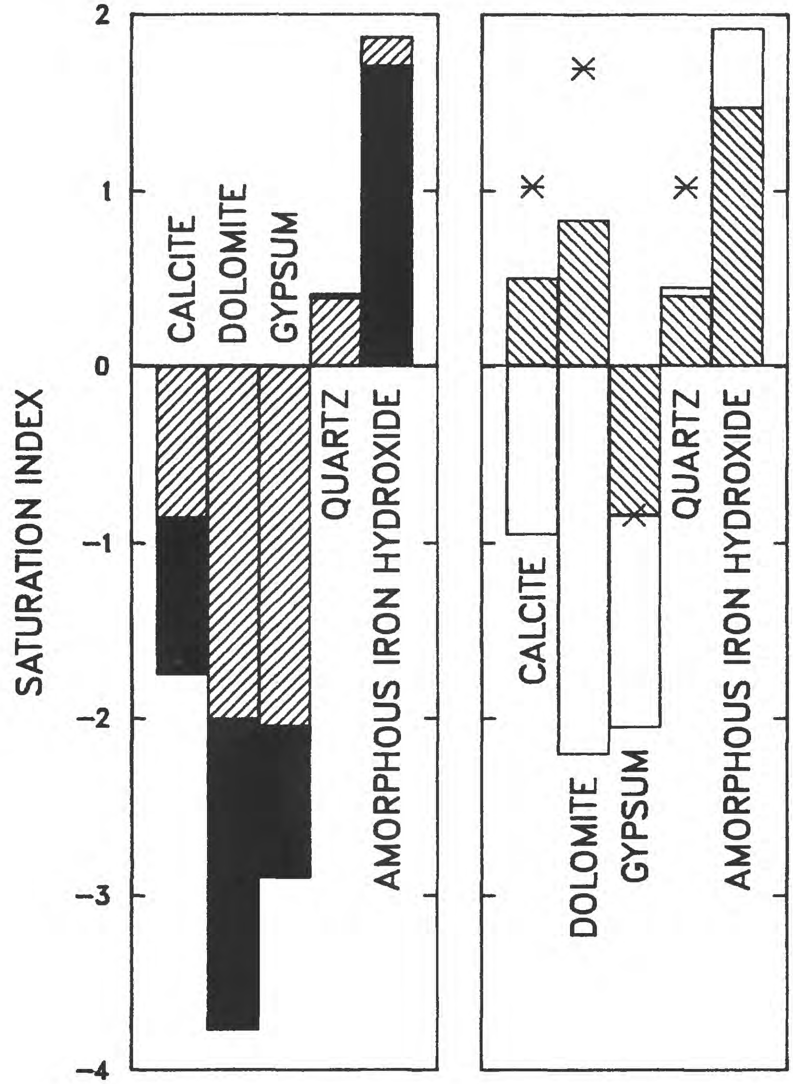


Figure 18.—Saturation indices of WATEQF mineral equilibrium and solubility calculations for selected samples collected at stream-gaging stations in the Hay Creek watershed.



EXPLANATION

- MEAN FOR UPSTREAM GAGING STATION 06340524
- MEAN FOR DOWNSTREAM GAGING STATION 06340528
- VALUE FOR DISCHARGE LESS THAN 0.2 CUBIC FOOT PER SECOND AT STREAM-GAGING STATION 06340528
- MEAN FOR DISCHARGE GREATER THAN 0.2 CUBIC FOOT PER SECOND AT STREAM-GAGING STATION 06340528
- ✳ VALUE FOR GROUND WATER (CRAWLEY AND EMERSON, 1981, p. 44)

Figure 19.—Saturation indices of WATEQF mineral equilibrium and solubility calculations for selected samples collected at stream-gaging stations in the West Branch Antelope Creek watershed.

For the downstream gaging station 06336515 along Hay Creek, low-flow water is closer to saturation with respect to gypsum than the high-flow water. Both low- and high-flow water are almost saturated with respect to calcite, dolomite, and quartz. Although trends in the saturation indices for calcite and dolomite are consistent with a possible increase in ground-water contribution to streamflow during low flow, the trend in the saturation indices for gypsum is opposite that expected from an increased ground-water contribution. The fact that all saturation indices indicate almost complete saturation during low-flow periods indicates evaporative concentration of solutes may be the dominant process affecting water quality.

The Piper diagrams for West Branch Antelope Creek indicate a small relative downstream increase in sodium and sulfate (fig. 17). For stream-gaging station 06340524, the dominant constituents are calcium, magnesium, and bicarbonate. Calcium never exceeded 49 percent of the cations and magnesium never exceeded 44 percent. Bicarbonate never exceeded 82 percent of the anions. For stream-gaging station 06340528, the dominant constituents are calcium, magnesium, bicarbonate, and sulfate. Calcium never exceeded 44 percent of the cations and magnesium never exceeded 35 percent. Bicarbonate never exceeded 81 percent of the anions and sulfate never exceeded 67 percent.

The WATEQF speciation model indicates dissolution of calcite, dolomite, and gypsum probably occurs between the upstream gaging station 06340524 and the downstream gaging station 06340528 along West Branch Antelope Creek (fig. 18). An increase in sodium concentrations relative to concentrations of calcium and magnesium indicates an exchange of divalent cations for sodium on streambed sediments must have occurred. Amorphous iron hydroxide and quartz are oversaturated in all samples, indicating a stable equilibrium exists for processes involving these minerals.

For the downstream gaging station 06340528 along West Branch Antelope Creek, low-flow water is more saturated than high-flow water with respect to calcite, dolomite, and gypsum and less saturated with respect to amorphous iron hydroxide. Both low- and high-flow waters are saturated with respect to quartz. Trends in saturation indices for gypsum and quartz between low- and high-flow waters do not indicate that an increased ground-water contribution produced the water-quality changes. Instead, all saturation indices are consistent with evaporative concentrations being the principal control on water quality.

WATERSHED MODEL

Model Description

The digital watershed model used to simulate the Hay Creek and West Branch Antelope Creek hydrologic systems is the Precipitation-Runoff Modeling System developed by Leavesley and others (1983). The Precipitation-Runoff Modeling System is a modular-design modeling system that has been developed to evaluate the impacts of various combinations of precipitation, climate, and land use on surface-water runoff, sediment yields, and general basin hydrology. Normal and extreme rainfall or snowmelt or both can be simulated on various combinations of land use to evaluate changes in water-balance relationships, flow regimes, flood peaks and volumes, soil-water relationships, sediment yields, and ground-water recharge. The system is a deterministic physical-process modeling system. To reproduce the physical reality of the hydrologic system as closely as possible, each component of the hydrologic cycle is expressed in the form of physical laws or empirical relationships that have some physical interpretation based on measurable watershed characteristics. The general model structure and flow path are shown in figure 20.

The modular design of the modeling system provides a flexible modeling capability. Each component of the hydrologic system is defined by one or more subroutines that are maintained in a computer-system library. All subroutines are compatible for linkage to each other. Given a specific hydrologic problem and its associated data constraints, the user can select an established model from the library or can design his or her own model using selected library and user-supplied subroutines. The library also contains subroutines for parameter optimization, sensitivity analysis, and model-output handling and analysis. The initial system's subroutines were obtained by modularizing an event-type, distributed-routing rainfall-runoff model (Dawdy and others, 1978) and a daily flow rainfall- and snowmelt-runoff model (Leavesley, 1973). Additional subroutines will be added and existing subroutines will be modified and improved as experience is gained from model applications in various climatic and physiographic regions. The components and subroutines used for this report are those available at the time of the investigation.

The model system is designed to function as either a lumped- or distributed-parameter type system--that is, the basin is partitioned into subunits based on slope, aspect, vegetation type, soil type, and snow distribution. Each subunit is considered homogeneous with respect to its hydrologic response and is called a hydrologic-response unit (HRU). Partitioning into HRU's will help account for the temporal and spatial variations of the hydrologic characteristics, climatic variables, and system response. Partitioning also will provide the ability to impose land-use changes on parts or all of a basin and to evaluate the resulting hydrologic impacts on each HRU and on the total basin.

Input parameters to the model system include descriptive data on the physiography, vegetation, soils, and hydrologic characteristics of each HRU, and on the variation of climate over a basin. The minimum climatic data needed to run the model are: (1) Daily precipitation and (2) maximum and minimum daily air temperature. Daily solar radiation and pan evaporation can be input to improve computations of snowmelt runoff, snowpack evaporation, and potential evapotranspiration. The model system can be run in daily mode, storm (time interval less than daily) and daily mode, or storm and daily mode with flow routing, depending on hydrologic and basin variables or the required output. To simulate stormflow hydrographs, rainfall depths for time intervals of 15 minutes or less are required. As many as three rain gages can be used for precipitation input. The model system is designed to run with data retrieved directly from the U.S. Geological Survey's WATSTORE data storage and retrieval system. However, the model system also can use data not stored on the WATSTORE system. Programs are available to read and reformat these data to make them model compatible.

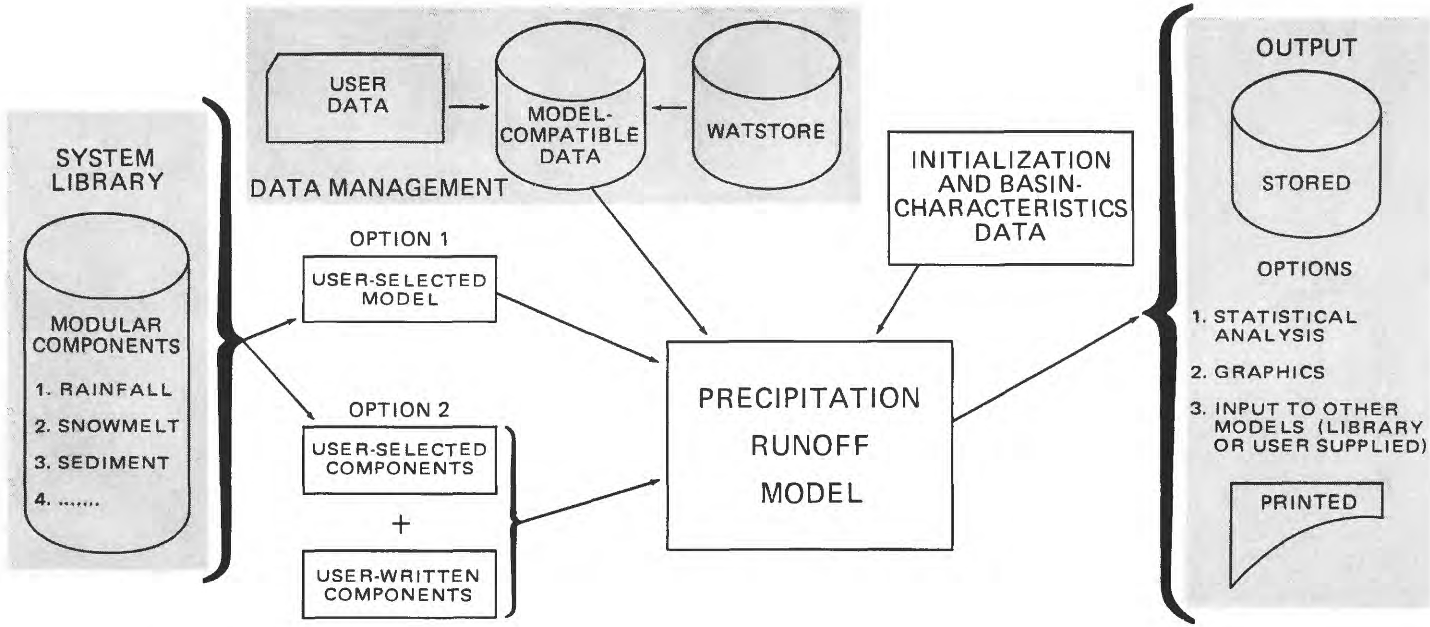


Figure 20.—Precipitation-runoff modeling system. (Modified from Leavesley and others, 1983, p. 4).

The model system has been developed on an AMDAHL[1/] computer system. However, the model components should run on any computer that uses the FORTRAN programing language. The only modifications that may be required on another computer system would be to the data-retrieval subroutines. The data-retrieval subroutines are written in PL/1 programing language to facilitate the handling of index-sequential file structures.

Daily Simulation Mode

The Precipitation-Runoff Modeling System was used to simulate the hydrologic cycle of both watersheds on a daily time scale. The daily mode simulates hydrologic components as daily averages or total values. The daily values or input time series used for daily simulations are daily precipitation, maximum and minimum daily air temperatures, and daily solar radiation. The data collected at the weather station in each watershed were used to run the simulations. A complete description of the weather stations and the listing of the data are presented in a report by Emerson and others (1983).

Because runoff in North Dakota is due mainly to snowmelt (Emerson, 1982) and because little runoff occurred during the study period, the daily simulations were made for periods that represented only the snow-accumulation and snowmelt periods. The simulated periods for the Hay Creek watershed are: (1) October 1, 1977, through March 31, 1978; (2) November 1, 1978, through April 17, 1979; (3) December 1, 1979, through March 14, 1980; and (4) November 1, 1980, through February 20, 1981. The simulated periods for the West Branch Antelope Creek watershed are: (1) November 1, 1977, through April 31, 1978; (2) November 1, 1978, through April 22, 1979; (3) November 1, 1979, through March 20, 1980; (4) November 1, 1980, through February 26, 1981; and (5) November 1, 1981, through April 18, 1982.

Parameter Estimation

By limiting the simulations to the snowmelt runoff, greater accuracy could be obtained by having the parameters optimized for only the winter period. The parameters that affect only rainfall runoff can be ignored and modeling costs reduced. The following discussion pertains only to snowmelt runoff.

Each HRU is characterized by its vegetation, soils, topography, and climate and is represented by parameter values. Some of these parameters have direct physical interpretation, others have less direct physical interpretation, and still others have very little or no physical interpretation. Some of the parameters were determined from intensive data collection, others were obtained from other investigations, and still others were estimated by best fit. The model-parameter names and definitions are listed in table 12.

[1/]The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

Table 12.-- *Model parameters*

Parameter	Definition
BST	Base temperature above which all precipitation is rain and below which all precipitation is snow (degrees Celsius or degrees Fahrenheit, depending on input data).
COVDNS	Summer vegetation-cover density for each HRU (decimal fraction).
COVDNW	Winter vegetation-cover density for each HRU (decimal fraction).
CTS	Air-temperature coefficient for evapotranspiration computation for months 1-12.
CTW	Proportion of potential evapotranspiration that is sublimated from a snowpack (decimal fraction).
CTX	Air-temperature coefficient for evapotranspiration computation for each HRU.
DENI	Initial density of new-fallen snow (grams per cubic centimeter).
DENMX	Average maximum snowpack density (grams per cubic centimeter).
DRCOR	Daily precipitation correction factor for rain for each HRU (decimal fraction).
DSCOR	Daily precipitation correction factor for snow for each HRU (decimal fraction).
EAIR	Emissivity of the air for longwave radiation on days without precipitation.
FWCAP	Free-water-holding capacity of the snowpack (decimal fraction).
GSNK	Coefficient to compute seepage rate from each ground-water reservoir to ground-water sink (inches per day).
GW	Storage in each ground-water reservoir (acre-inches).
IMPERV	Proportion of each HRU that is impervious (decimal fraction).
ITND	Month transpiration ends for each HRU.
ITST	Month to begin checking for start of transpiration for each HRU.

Table 12.-- *Model parameters*--Continued

Parameter	Definition
PARS	Correction factor for computed solar radiation on summer days with precipitation (decimal fraction).
PARW	Correction factor for computed solar radiation on winter days with precipitation (decimal fraction).
PAT	Maximum air temperature which, when exceeded, forces precipitation to be all rain (degrees Celsius or degrees Fahrenheit, depending on input data).
RCB	Routing coefficient for each ground-water reservoir.
RCF	Linear routing coefficient for each subsurface reservoir.
RCP	Nonlinear routing coefficient for each subsurface reservoir.
RDC	Y-intercept for relation between air temperature (x) and degree day (y) (degrees Celsius or degrees Fahrenheit, depending on input data).
RDM	Slope for relation between air temperature (x) and degree day (y) (degrees Celsius or degrees Fahrenheit, depending on input data).
REMX	Maximum available water-holding capacity of upper soil zone for each HRU (inches).
RES	Storage in each subsurface flow reservoir (acre-inches).
RETIP	Maximum retention storage on impervious area for each HRU (inches).
RMXA	Proportion of rain in a rain-snow event above which snow albedo is not reset for snowpack-accumulation stage (decimal fraction).
RMXM	Proportion of rain in a rain-snow event above which snow albedo is not reset for snowpack-melt stage (decimal fraction).
RNSTS	Interception storage capacity of unit area of vegetation for rain during summer period for each HRU (inches).
RNSTW	Interception storage capacity of unit area of vegetation for rain during winter period for each HRU (inches).

Table 12.-- *Model parameters*--Continued

Parameter	Definition
SCN	Minimum possible contributing area for surface runoff as proportion of each HRU area (decimal fraction).
SCX	Maximum possible contributing area for surface runoff as proportion of each HRU area (decimal fraction).
SEP	Seepage rate from soil-moisture excess to each ground-water reservoir (inches per day).
SETCON	Snowpack-settlement-time constant.
SMAX	Maximum available water-holding capacity of soil profile for each HRU (inches).
SNST	Interception storage capacity of unit area of vegetation for snow for each HRU (inches of water equivalent).
SRX	Maximum daily snowmelt-infiltration capacity of soil profile at field capacity for each HRU (inches).
TLN	Lapse rate for daily minimum temperature for months 1-12 (degrees Celsius or degrees Fahrenheit per 1,000 feet, depending on input data).
TLX	Lapse rate for daily maximum temperature for months 1-12 (degrees Celsius or degrees Fahrenheit per 1,000 feet, depending on input data).
TNAJ	Adjustment for minimum air temperature for slope and aspect for each HRU (degrees Celsius or degrees Fahrenheit, depending on input data).
TRNCF	Transmission coefficient for shortwave radiation through the winter-vegetation canopy for each HRU (decimal fraction).
TST	Accumulated daily maximum temperature value for month ITST at which transpiration begins for each HRU.
TXAJ	Adjustment for maximum air temperature for slope and aspect for each HRU (degrees Celsius or degrees Fahrenheit, depending on input data).

Best fit of estimated parameters was determined by model simulation using the optimization and sensitivity options of the model. To obtain the best fit--better agreement between measured and predicted runoff--a subroutine using the Rosenbrock optimization technique was used to obtain an optimal set of parameter values. The Rosenbrock optimization technique is described in detail in a paper by Rosenbrock (1960) and discussed in a hydrologic context by Dawdy and O'Donnell (1965) and Dawdy, Lichty, and Bergmann (1972). An absolute difference form of the objective function was used to measure the agreement between measured and predicted runoff as shown in equation 1:

$$\text{Objective function} = \sum_{i=1}^{\text{days}} \left| \text{measured discharge}_i - \text{predicted discharge}_i \right| \qquad (1)$$

Parameters relating to evaporation and transpiration are CTS, CTX, CTW, TST, ITST, and ITND. The Jensen-Haise equation (Jensen and Haise, 1963) consisting of two air temperature coefficients, CTS and CTX, was used to compute potential evapotranspiration. Values of CTS and CTX were computed using meteorological data. The values for Hay Creek are 0.012 for CTS and 19.10 for CTX, and the values for West Branch Antelope Creek are 0.012 for CTS and 19.18 for CTX. These values are good estimates of CTS and CTX for summer potential evapotranspiration for which the Jenson-Haise equation was developed. Sensitivity analysis indicated that the parameters CTS and CTX were not very sensitive for snowmelt runoff; therefore, these values were used.

Sublimation from the snowpack is computed as a fraction (CTW) of the potential evapotranspiration. Because the Jenson-Haise equation (Jensen and Haise, 1963) was developed to compute summer potential evapotranspiration and does not represent the evaporation or sublimation of a snowpack, CTW was set to 0. If CTW is increased, the values of CTS and CTX would have to be changed in order that a reasonable value for sublimation is produced during the winter; then the evaporation computed during the melt period would be an order of magnitude too large.

The month in which transpiration starts is specified by ITST, and the month in which it ends is specified by ITND. A value of 4 was used for ITST, and a value of 10 was used for ITND. A value for each of these parameters was input for each HRU, but for North Dakota's climatology, the variation was insignificant. The specific date of the start of transpiration is computed using the temperature-index parameter, TST. The sum of the daily maximum temperatures is cumulated starting with the first day of ITST. When the sum exceeds TST, transpiration is assumed to begin. This technique permits accounting, in part, for warmer- or colder-than-normal springtime periods. A value of 700 was computed for TST based on the data from the study areas.

The model includes a technique for estimating missing solar radiation. The technique uses a maximum-air-temperature relationship requiring a slope (RDM) and an intercept (RDC) and two correction factors for summer and winter days with precipitation (PARS and PARW). This technique was found to be very poor at estimating missing solar radiation. Instead, linear-regression equations based on solar-radiation data obtained from the National Weather Service in Bismarck, N. Dak., and solar-radiation data for Hay Creek and West Branch Antelope Creek were developed for each month. The equations (table 13) for Hay Creek produced fair estimates of missing solar radiation and the equations for West Branch Antelope Creek produced good estimates. Values of missing solar radiation can be computed and read in along with the observed data. Therefore, the parameter values RDM, RDC, PARS, and PARW are not used because solar-radiation data for Bismarck can be used to predict solar radiation better than a technique based on an air-temperature relationship.

The air temperature for each HRU can be corrected for aspect and elevation. Since the change in elevation from the headwaters to the basin outlet is small--270 ft for Hay Creek and 360 ft for West Branch Antelope Creek--correction parameters TNAJ, TXAJ, TLN, and TLX are not needed and were set to 0.

Precipitation in the form of rain, snow, or mixed rain and snow is estimated by using maximum and minimum daily air temperature and a base temperature (BST). BST is the temperature above which all precipitation is rain and below which all precipitation is snow. When maximum daily air temperature (TM) is less than or equal to BST, then all precipitation is considered to be snow. When minimum daily air temperature (TN) is greater than or equal to BST, then all precipitation is considered to be rain. When TM is greater than BST and TN is less than BST, the precipitation is considered to be a mixture of rain and snow based on maximum and minimum daily air temperature and BST. According to the U.S. Army Corps of Engineers (1956, p. 55), a value of 1.0 °C for BST would correctly designate the form of precipitation in 90 percent of the cases. PAT is the maximum air temperature which, when exceeded, forces all spring and summer precipitation to be rain. The parameter PAT was found not to be very sensitive and, therefore, a value of 5.0 °C was used.

The density of new-fallen snow (DENI) generally is assumed to be 0.10 g/cm^3 (gram per cubic centimeter; U.S. Army Corps of Engineers, 1956, p. 288). Densities of new-fallen snow vary with surface wind and range from 0.06 g/cm^3 for snow deposited during calm conditions to 0.34 g/cm^3 for snow deposited during gale winds. Changes in density of new-fallen snow are rapid and variable during the first few hours after deposition. Therefore, considering the wind factor and the changes after the first few hours, an assumed average density of new-fallen snow of 0.20 g/cm^3 is used for model application. Sensitivity analysis indicated that the model was not sensitive to DENI except when snowfall occurred just before snowmelt and then the model was only mildly sensitive. The maximum snowpack density (DENMX) was estimated to be between 0.30 and 0.35 g/cm^3 based on 251 density measurements made during the study. Snowpack-settlement-time constant (SETCON) was found not to be very sensitive and a value of 0.10 was used as suggested by Riley and others (1973). The U.S. Army Corps of Engineers (1956, p. 303) recommended using values of between 2 to 5 percent by weight for the free-water-holding capacity of snowpack (FWCAP). They also stated that these values are used for free drainage of the snowpack. In flat areas, free-water-holding capacity may far exceed free drainage. Therefore, a variation in the definition of FWCAP

Table 13.-- *Regression equations for predicting solar radiation*

[Solar radiation = A+Bx (solar radiation at Bismarck)]

	Hay Creek				West Branch Antelope Creek			
Month	A	B	Standard deviation	R^2	A	B	Standard deviation	R^2
1	35.27	0.74	39.44	0.44	-24.08	1.22	24.65	0.85
2	58.77	.68	55.42	.46	23.56	.91	34.23	.79
3	116.64	.62	79.90	.34	67.32	.78	53.21	.65
4	50.90	.86	92.47	.67	100.92	.81	66.21	.77
5	180.12	.62	107.77	.46	18.65	.94	69.07	.82
6	223.10	.61	109.29	.37	153.13	.78	82.94	.63
7	279.80	.55	86.68	.41	122.59	.83	89.16	.65
8	247.65	.47	130.80	.09	101.63	.85	107.21	.47
9	54.88	.88	78.95	.62	27.81	.97	44.17	.87
10	127.93	.53	58.14	.38	61.05	.86	29.31	.86
11	82.04	.54	39.60	.38	31.79	.88	30.03	.74
12	19.03	.88	33.07	.39	-1.37	1.15	30.15	.61

is needed for the prairie. During short periods without runoff prior to the main snowmelt-runoff period, as much as 60 percent of the snowpack water equivalent has been retained in storage on top of frozen soil. This type of storage was found only on relatively flat areas with shallow snow depths. Male and Granger (1978, p. 120) indicated that in a prairie environment the initial melt period where snow cover is continuous does not produce significant runoff, and ponding water appears. In the northern Great Plains, runoff is not significant until 20 to 30 percent of the watershed is bare. To account for these two situations, FWCAP was increased to 35 percent.

Rain mixed with snow is rare in North Dakota and, if it does occur, usually occurs after the snowmelt period. Therefore, the value for the parameter RMXA is the proportion of rain in a rain-snow storm above which snow albedo is not reset in a snowpack-accumulation stage. The value for the parameter RMXM is the proportion of rain in a rain-snow storm above which snow albedo is not reset for a snowpack-melt stage. This treatment of mixed precipitation will not create serious errors. Values of 0.20 for RMXA and 0.50 for RMXM were estimated.

The emissivity (EAIR) is the ratio of back radiation from the Earth's atmosphere to the theoretical black-body radiation computed using surface air temperature. Several investigators have proposed equations wherein emissivity is correlated with surface vapor pressure (U.S. Army Corps of Engineers, 1956, p. 157-159). A value of 0.757 generally is accepted for emissivity of extensive snowfields during melting of a snowpack. Other investigators determined values of emissivity for these conditions varying from 0.579 to 0.769. The value 0.757 was determined for melt conditions of extensive snowfields, which are not the general conditions throughout the winter in North Dakota. Values ranging from 0.733 to 0.873 were determined for emissivity using the Rosenbrock optimization procedure. The sensitivity analysis indicated that the model was very sensitive to EAIR.

The watershed system is described as a series of reservoirs (fig. 21) with the outputs combined to produce the system response. The soil profile is a reservoir where storage is increased by rainfall or snowmelt and depleted by evapotranspiration and seepage to the subsurface reservoir. The depth of the soil profile is considered to be the average rooting depth of the dominant

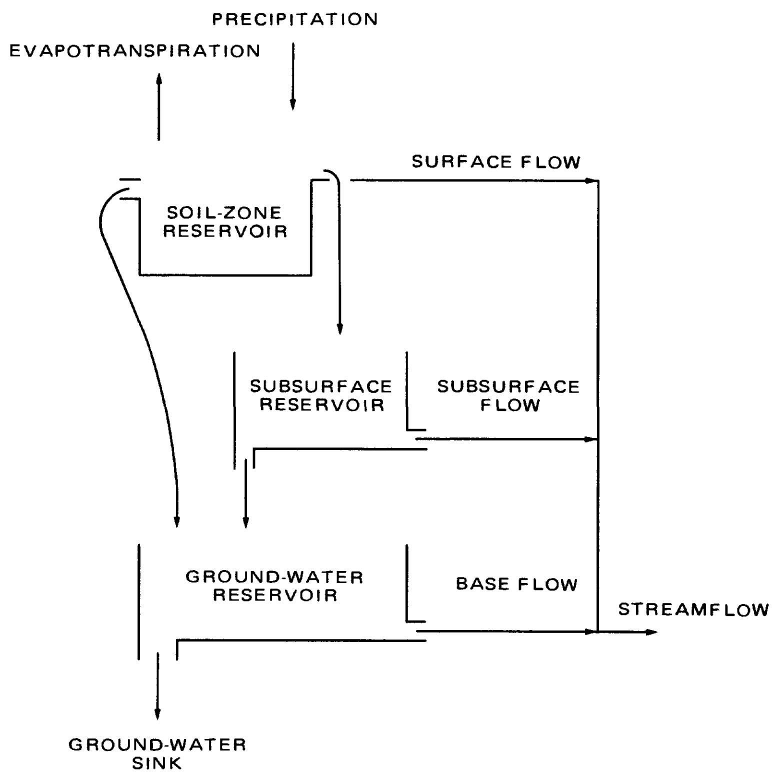


Figure 21.—Schematic diagram of watershed model.

vegetation in each HRU. The soil profile has an upper and lower soil zone. Evaporation and transpiration occur from the upper zone, but only transpiration occurs from the lower zone. Moisture in the soil-profile reservoir seeps to the subsurface reservoir only after the soil-profile reservoir reaches field capacity and, in turn, moisture in the subsurface reservoir seeps to a ground-water reservoir. Surface runoff occurs when rainfall exceeds the maximum infiltration rate or when snowmelt exceeds the maximum daily infiltration value. Subsurface flow is the movement of water through the soil mantle to some point of discharge. Flow from the ground-water reservoir is either base flow to the stream or to a ground-water sink, a point beyond the area of interest.

The parameters used in soil moisture accounting are SMAX, REMX, SRX, SEP, RCF, RCP, and RCB. SMAX is the maximum available water-holding capacity of the soil profile and is the difference between the moisture at field capacity (1/3 bar) and the permanent wilting point (15 bars). REMX is the maximum available water-holding capacity of the upper soil zone. These parameters were estimated from the Beulah Trench report (U.S. Department of the Interior, 1977) and from analysis of soil profiles.

SRX is the maximum daily infiltration parameter. SRX is not a physically-based parameter and was determined by using the Rosenbrock optimization procedure. The value for SRX ranged from 0.25 to 0.33.

SEP is the constant seepage volume of excess moisture from the soil profile to the ground-water reservoir, GW. The remainder of excess moisture from the soil profile seeps to the subsurface reservoir, RES. RCF and RCP are subsurface-flow routing coefficients and RCB is the ground-water-flow routing coefficient. GSNK is a coefficient used in computing the seepage rate from a ground-water reservoir to a ground-water sink. SEP, RCF, RCP, RCB, and GSNK were very sensitive and were determined by using the Rosenbrock optimization procedure. Values of 0.28, 0.0001, 0.01, 0.004, and 0.09 were used for SEP, RCF, RCP, RCB, and GSNK, respectively.

The maximum (SCX) and minimum (SCN) possible contributing area as a proportion of the total HRU is input for each HRU. These values vary depending on the characteristics of each HRU. Values for SCX ranged from 0.03 to 1.00. Values for SCN ranged from 0.50 to 0.

IMPERV is the effective impervious area as a proportion of the total HRU area. Although there are a few roads and farm buildings that are impervious areas, these areas are relatively small and IMPERV was set to 0. The maximum retention storage on an impervious area (RETIP) also was set to 0.

Interception varies with vegetation type and canopy density and with precipitation type. These factors are used to determine interception for each HRU. Winter density of the predominant vegetation cover above the snowpack (COVDNW) is expressed as a percent of the HRU surface covered by horizontal projection of the vegetation canopy. For most areas in the Fort Union coal region of Montana and North Dakota, COVDNW is 0. Generally, the only exceptions would be HRU's that consist mainly of shelterbelts or of river channels that are predominantly tree covered. For these areas, COVDNW would be between 0 and 0.10. Winter-interception storage capacity for rain (RNSTW), expressed in inches of water equivalent, and winter-interception storage capacity for snow (SNST), expressed in inches of water equivalent, are the quantity of water that can be stored on the foliage, branches, and stem of the predominant vegetation of the HRU. RNSTW and SNST are negligible for grass, and values were estimated to be 0 for both parameters.

The transmission coefficient for the vegetation canopy over the snowpack (TRNCF), expressed in percent, is a function of canopy density, crown depth, size of tree crown, species, and season. TRNCF was set to 1.00 for most areas and near 1.00 for areas of tree cover.

The summer vegetation-cover density (COVDNS) and summer-interception storage capacity of major vegetation (RNSTS) for each HRU are not used in computing snowmelt. The values for COVDNS and RNSTS vary throughout the summer and from year to year. Much of the area is cropland and vegetation-cover density varies from bare soil during planting to small sprouts to dense crop fields prior to harvest. Also, the growing condition can have a major effect on crops and pastures.

Partitioning of Watersheds

Each watershed was partitioned into a number of HRU's based on slope, aspect, vegetation type, soil type, and snow distribution. The criteria for partitioning a watershed into HRU's is subjective. For the Fort Union coal region, partitioning can be based primarily on snow distribution, thereby taking many of the other criteria into consideration.

The optimum number of HRU's for the Rocky Mountain region was between 15 and 22 (Leavesley, 1973, and Weeks and others, 1974). The optimum number of HRU's for the northern prairie needs to be determined. The Hay Creek and West Branch Antelope Creek watersheds were first partitioned into 23 and 36 HRU's, respectively (figs. 22 and 23). The West Branch Antelope Creek watershed also was partitioned into 18, 9, and 1 HRU's. Partitioning schemes were accomplished by grouping HRU's as listed in table 14.

Snowmelt Simulation

Model simulations were made for each partitioning scheme. The hydrographs of the measured and simulated mean daily streamflows are shown in figures 24 and 25. The runoff periods represent a wide range in snow accumulation and melt periods. The values for objective function (absolute value of the difference in total measured runoff and total simulated runoff), EAIR, and SMAX-SMAV for each simulation are listed in table 15.

In general, 36 HRU's produced the best results for West Branch Antelope Creek. The large differences in values for objective function and difference in total runoff for 1979 indicate that the model is sensitive to the degree in which the watershed is partitioned. This sensitivity is due mainly to snow distribution. The snow distribution is defined best for the 1978-79 winter with the model simulation reflecting it. For low snow-accumulation periods of 1979-80 and 1980-81, when variation in snow distribution was not very

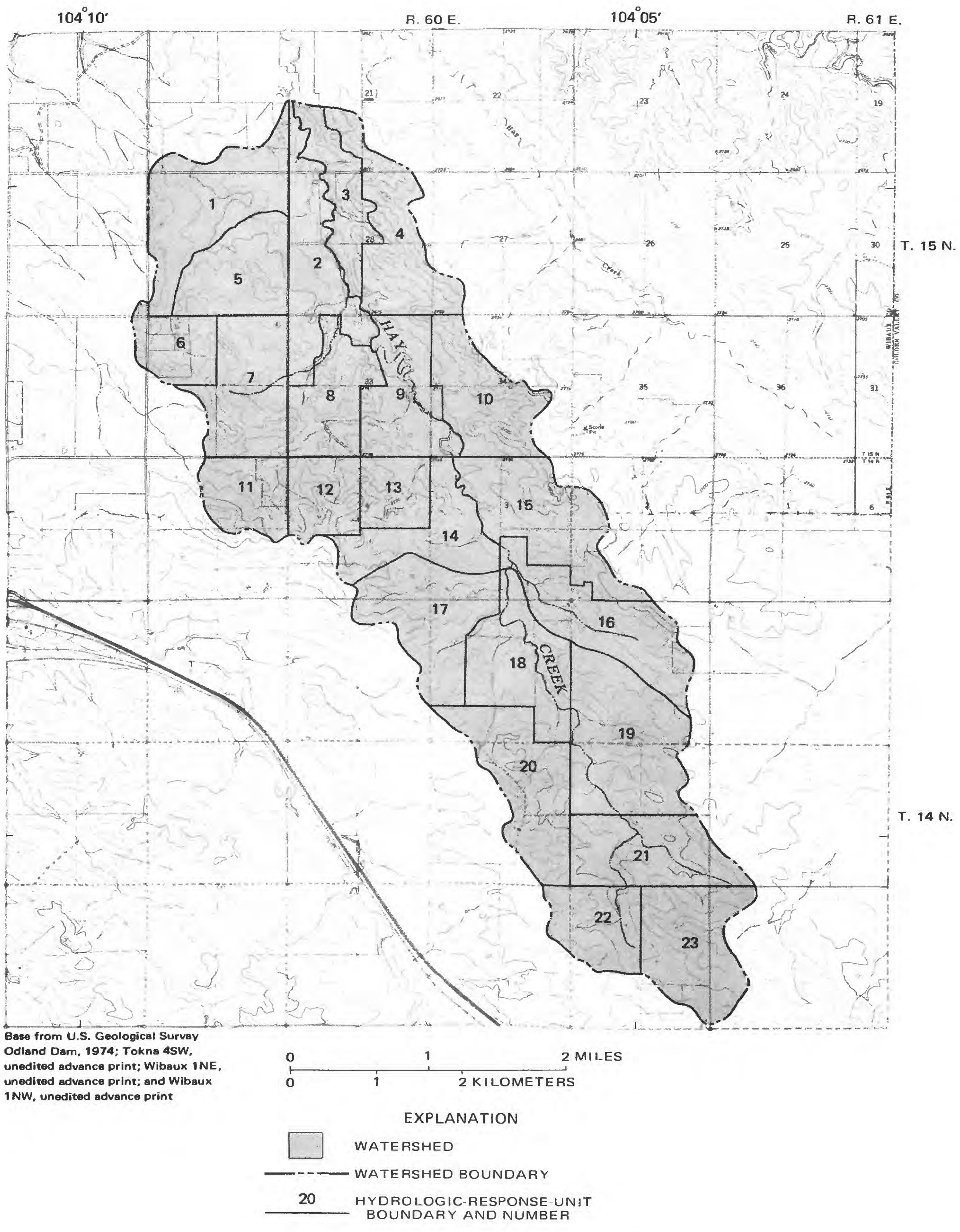


Figure 22.—Hydrologic-response units in the Hay Creek watershed.

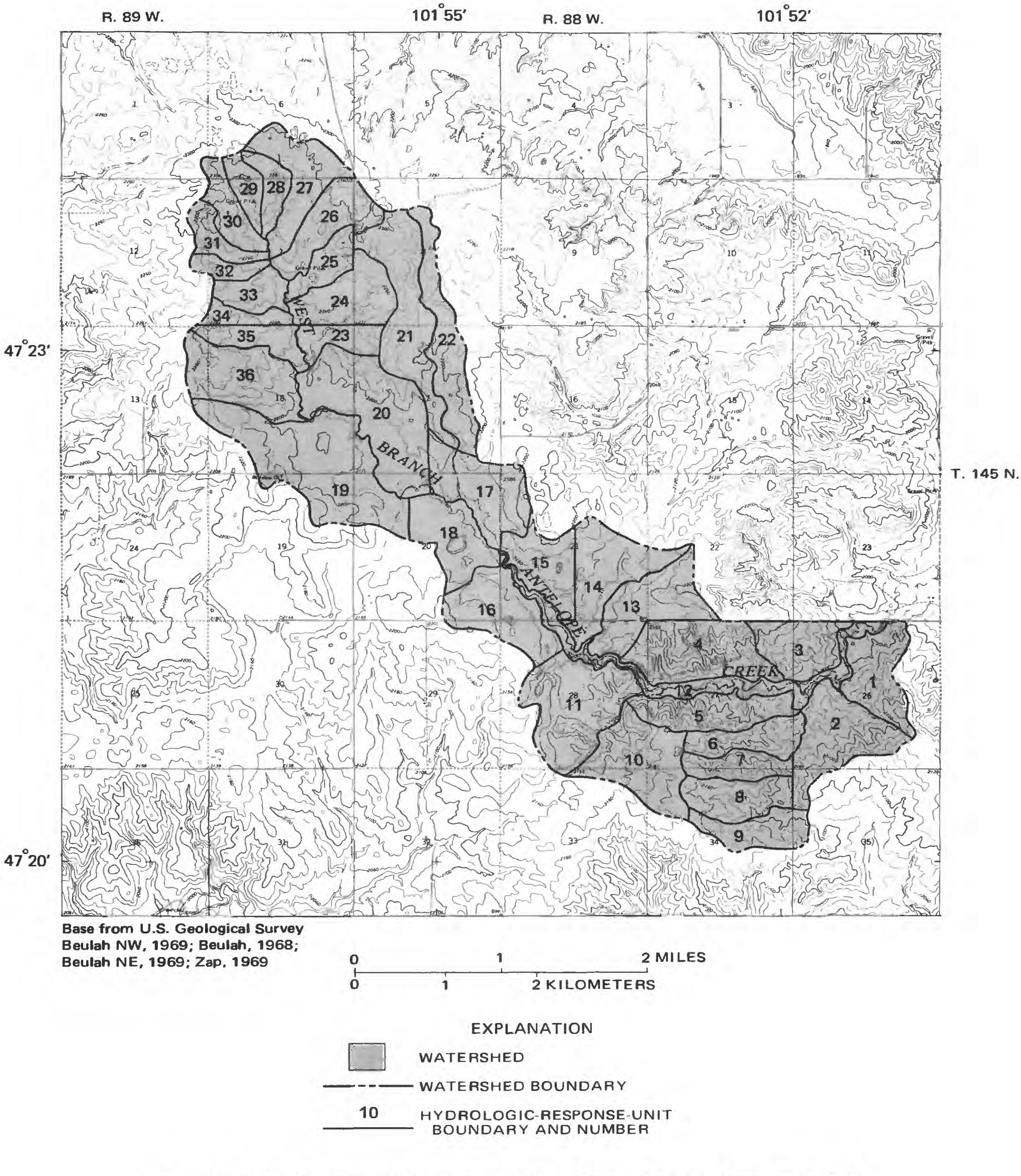


Figure 23.—Hydrologic-response units in the West Branch Antelope Creek watershed.

Table 14.-- *Summary of partitioning West Branch Antelope Creek watershed into various groupings of hydrologic-response units*

36 units		18 units		9 units		1 unit	
New unit	Original unit	New unit	Original units	New unit	Original units	New unit	Original units
1	--	1	1, 2, and 9	1	1, 2, 5, 7, and 9	1	1 to 36
2	--	2	3, 6, and 8	2	3, 4, 6, and 8		
3	--	3	4	3	12		
4	--	4	5 and 7	4	10, 11, and 16		
5	--	5	10 and 11	5	13, 14, and 15		
6	--	6	12	6	17, 18, 19, and 20		
7	--	7	13 and 14	7	21 and 22		
8	--	8	15	8	23, 25, 27, 28, 30, 32, and 34		
9	--	9	16	9	24, 26, 29, 31, 33, 35, and 36		
10	--	10	17 and 20				
11	--	11	18 and 19				
12	--	12	21				
13	--	13	22				

Table 14.-- *Summary of partitioning West Branch Antelope Creek watershed into various groupings of hydrologic-response units*--Continued

36 units		18 units		9 units		1 unit	
New unit	Original unit	New unit	Original units	New unit	Original units	New unit	Original units
14	--	14	23 and 25				
15	--	15	24, 26, and 27				
16	--	16	28, 30, 32, and 34				
17	--	17	29, 31, 33, and 35				
18	--	18	36				
19	--						
20	--						
21	--						
22	--						
23	--						
24	--						
25	--						
26	--						

Table 14.-- *Summary of partitioning West Branch Antelope Creek watershed into various groupings of hydrologic-response units*--Continued

36 units		18 units		9 units		1 unit	
New unit	Original unit	New unit	Original units	New unit	Original units	New unit	Original units
27	--						
28	--						
29	--						
30	--						
31	--						
32	--						
33	--						
34	--						
35	--						
36	--						

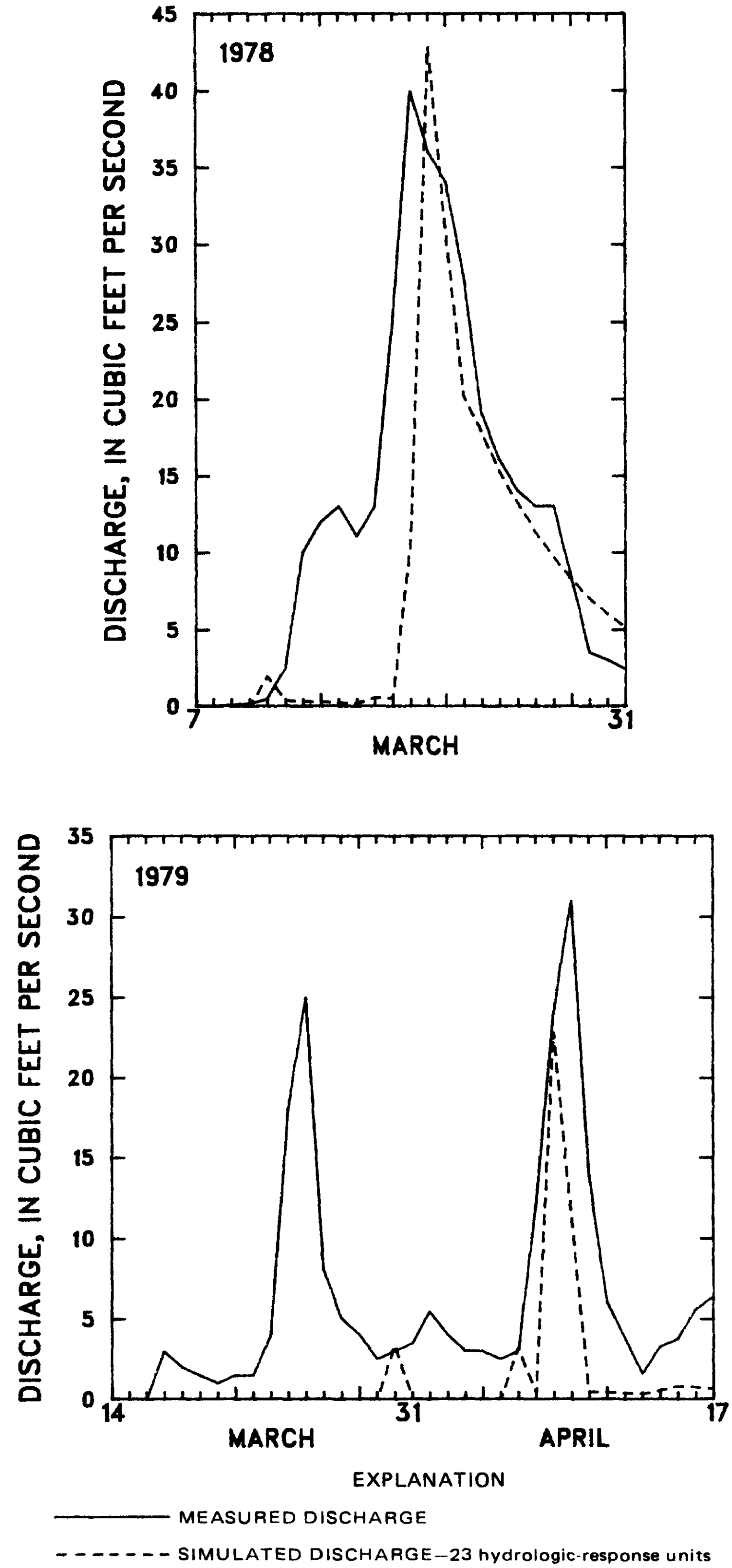
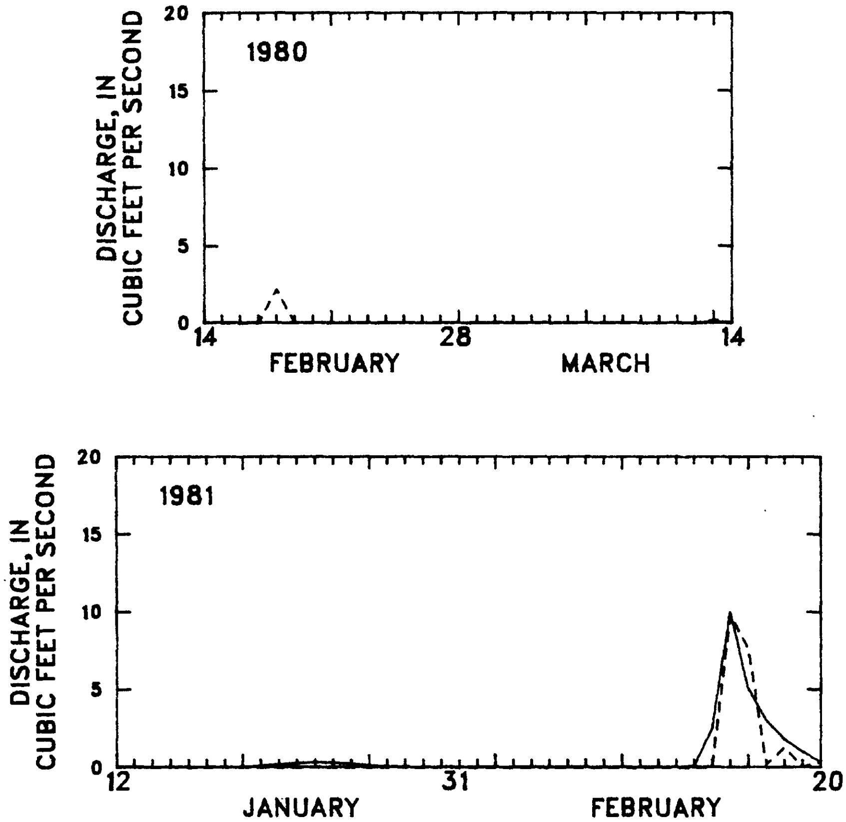


Figure 24.—Measured and simulated daily discharges for stream-gaging station 06336515, Hay Creek.



EXPLANATION

——— MEASURED DISCHARGE

- - - - SIMULATED DISCHARGE—23 hydrologic-response units

Figure 24.—Measured and simulated daily discharges for stream-gaging station 06336515, Hay Creek--Continued.

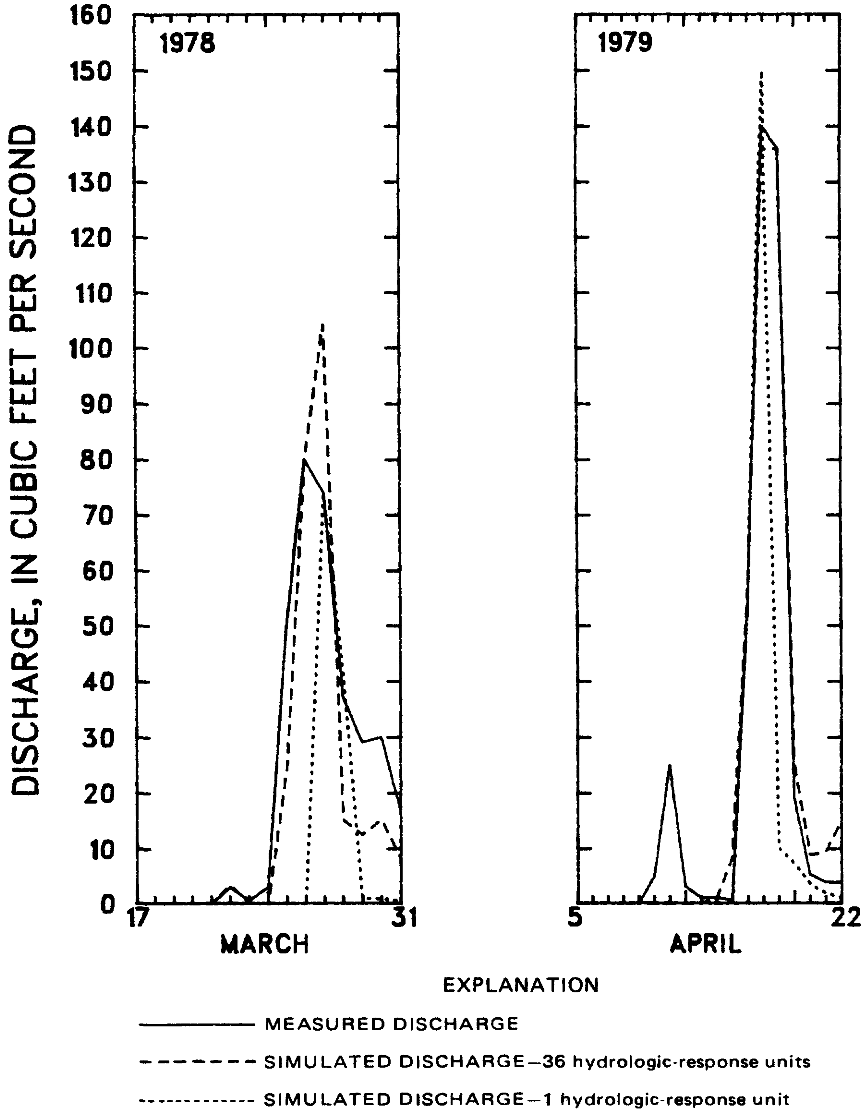


Figure 25.—Measured and simulated daily discharges for stream-gaging station 06340528, West Branch Antelope Creek.

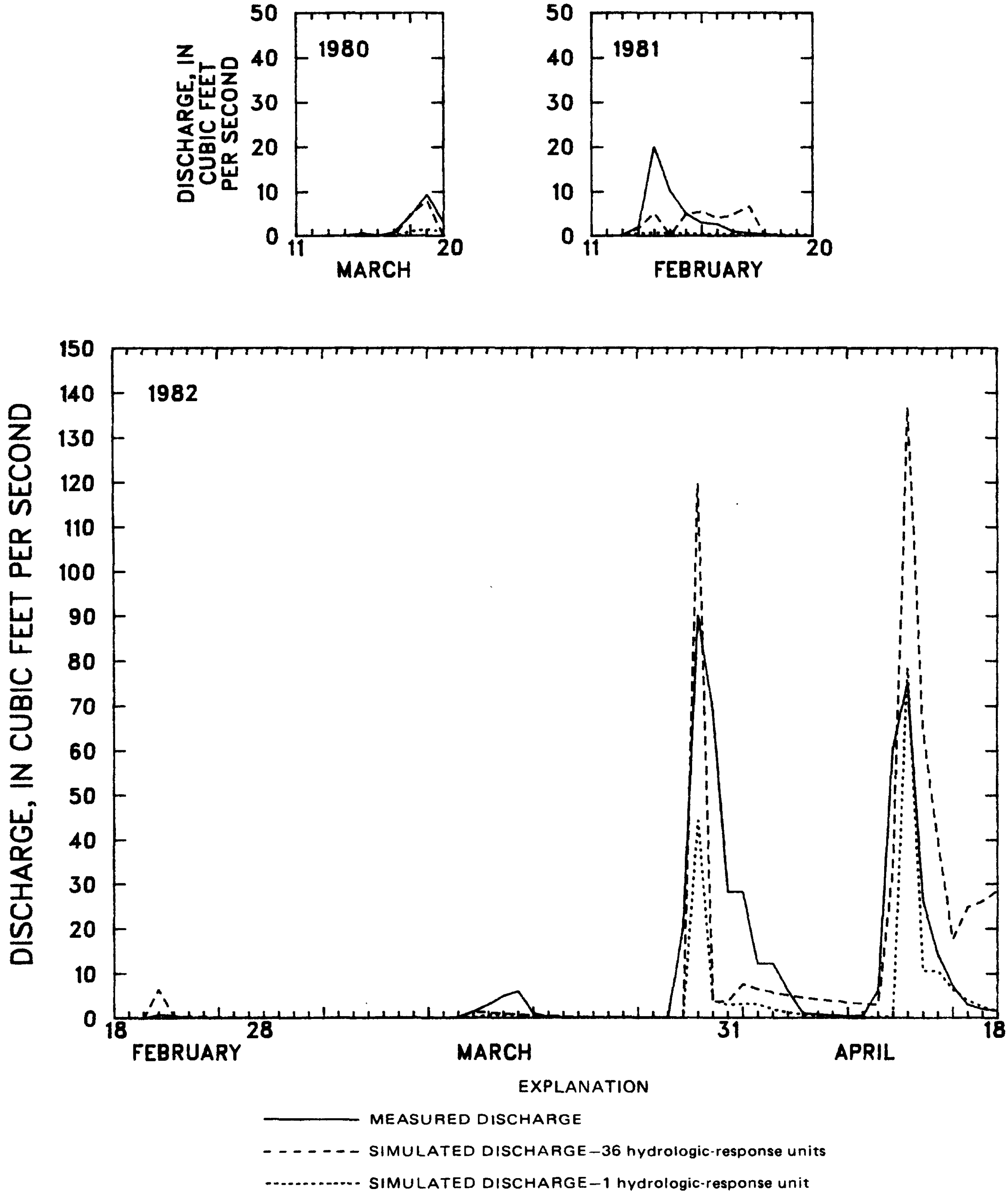


Figure 25.—Measured and simulated daily discharges for stream-gaging station 06340528, West Branch Antelope Creek--Continued.

Table 15.-- *Summary of simulation results for the Hay Creek and West Branch Antelope Creek watersheds*

Year	Number of hydrologic-response units	Cubic feet per second: Total measured runoff	Cubic feet per second: Total simulated runoff	Objective function	SMAX-SMAV (inches)	EAIR
		Hay Creek watershed				
1978	23	146.79	201.75	146.79	2.00	0.760
1979	23	25.47	19.18	171.51	3.00	.798
1980	23	.24	2.78	2.84	2.80	.859
1981	23	216.10	45.66	11.40	.78	.733
		West Branch Antelope Creek watershed				
1978	36	323.50	262.70	122.02	1.91	.860
1978	18	323.50	254.75	124.75	1.90	.857
1978	9	323.50	292.40	127.64	1.99	.846
1978	1	323.50	117.75	215.19	2.96	.846
1979	36	396.30	399.67	76.59	2.63	.844
1979	18	396.30	403.73	110.85	2.63	.837
1979	9	396.30	444.89	149.81	2.63	.835
1979	1	396.30	226.47	189.89	2.91	.863
1980	36	18.57	12.67	6.49	3.69	.844
1980	18	18.57	7.69	12.05	3.00	.892
1980	9	18.57	17.63	6.78	3.00	.873
1980	1	18.57	3.42	15.15	2.10	.873
1981	36	43.00	33.24	39.88	2.91	.830
1981	18	43.00	62.58	42.49	1.66	.830
1981	9	43.00	80.24	57.75	1.68	.825
1981	1	43.00	5.49	40.76	2.27	.857
1982	36	481.93	558.22	446.11	3.50	.845
1982	18	481.93	454.18	395.39	3.00	.8445
1982	9	481.93	537.55	530.39	3.00	.850
1982	1	481.93	179.39	313.09	2.38	.844

great, the model was not as sensitive to the degree in which the watershed was partitioned. This was indicated by the smaller differences in values for objective function and difference in total runoff. Therefore, partitioning of a watershed is a function of the degree of variation in snow distribution and how well the variation in snow distribution can be defined.

A sensitivity analysis showed that the parameters BST, DENMX, EAIR, FWCAP, SMAX, and SRX contribute the most to prediction error. Of these parameters, EAIR and SMAX are by far the most sensitive during the snowmelt period. The extent to which parameter uncertainty is, on the average, propagated to uncertainty in runoff prediction is examined. The results are displayed in an error propagation table (table 16) that gives an error value for each parameter at the 10-percent level. For example, a value of 150.0 would mean that a 10-percent error in the given parameter results in an increase of 150.0 in the mean square error of prediction for the model. The units of the values in table 16 are in cubic feet per second squared $[(ft^3/s)^2]$ and need to be compared to the mean square error of prediction (a residual variance). The residual variance in table 16 is computed by squaring the difference between the measured and the predicted runoff, and dividing by n-p (where n is the number of days and p is the number of parameters).

Model Analysis

The sensitivity analysis indicates the model is most sensitive to EAIR, which is used for computing longwave radiation. The model assumes that the sky is clear when it computes longwave radiation, which may be one reason why the value for EAIR is greater than that reported in most of the literature. Another reason may be because EAIR is compensating for other energy-budget components that are not accounted for in the model.

For a single snowmelt-runoff period as in 1979 for the West Branch Antelope Creek watershed, the energy budget of the model was adequate. However, for multiple snowmelt-runoff periods as in 1982 for the West Branch Antelope Creek watershed, more energy components, such as sensible- and latent-heat components, are needed to adequately simulate the snowmelt.

The model computes evaporation and sublimation of the snowpack by using a percentage of the potential evapotranspiration. The potential evapotranspiration is computed using the Jensen-Haise technique, which was developed for computing evapotranspiration for the summer months and, hence, did not take into account evaporation and sublimation from the snowpack. Methods that can better compute evaporation and sublimation from the snowpack usually require daily wind-velocity and relative-humidity data. Such methods could be added to the model system, but wind-velocity and relative-humidity data are not available for most watersheds.

The model does not have the capability of simulating the effects of frozen soils. The parameter IMPERV is the effective impervious area as a proportion of the total HRU area. IMPERV was used to try to simulate frozen soil. However, the values for IMPERV were constant throughout the simulation period, and the method did not reflect the freezing and thawing of the soil.

Table 16.-- *Ten-percent parameter error propagation summary*[1] *for the Hay Creek and West Branch Antelope Creek watersheds*

[HRU, hydrologic-response unit; BST, base temperature; CTS, air-temperature coefficient for months 1-12; CTX, air-temperature coefficient for each HRU; DENI, initial density of new-fallen snow; DENMX, average maximum snowpack density; EAIR, emissivity of air; FWCAP, free-water-holding capacity of the snowpack; RCB, routing coefficient for each ground-water reservoir; RCF, linear routing coefficient for each subsurface reservoir; RCP, nonlinear routing coefficient for each subsurface reservoir; REMX, maximum available water-holding capacity of upper soil zone; SEP, seepage rate; SETCON, snowpack-settlement-time constant; SMAX, maximum available water-holding capacity of soil profile; SRX, maximum daily snowmelt-infiltration capacity of soil profile]

Year	Number of HRU's	BST	CTS	CTX	DENI	DENMX	EAIR	FWCAP	RCB	RCF	RCP	REMX	SEP	SETCON	SMAX	SRX	Residual variance
							Hay Creek watershed										
1978	23	31.548	0.018	0.019	0.002	29.381	107.810	29.850	0.000	0.040	0.000	0.054	0.006	0.000	6.636	0.231	24.903
1979	23	.002	.000	.000	.020	28.216	395.380	.213	.000	.000	.000	.000	.000	.007	3.120	.021	12.326
1980	23	.003	.000	.000	.000	.000	.859	.000	.000	.000	.000	.000	.000	.000	.000	.000	.080
1981	23	.000	.000	.000	.000	.000	9.226	.028	.000	.000	.000	.000	.000	.000	.000	.426	.252
							West Branch Antelope Creek watershed										
1978	36	.000	.000	.000	132.106	131.730	467.835	.100	.000	.000	.000	.000	.000	132.104	48.286	.205	18.097
1978	18	.000	.000	.000	.000	.262	410.954	.122	.000	.000	.000	.000	.000	.000	70.454	.236	18.631
1978	9	.010	.000	.000	.000	.243	310.767	.358	.000	.000	.000	.000	.000	.000	87.388	.341	26.102
1978	1	.000	.000	.000	.000	.382	664.127	.248	.000	.000	.001	.000	.000	.000	157.127	.729	73.796
1979	36	1,027.655	.000	.000	.092	1.540	893.098	1.412	.000	.000	.000	.000	.000	.020	21.343	.202	5.672
1979	18	1.656	.000	.000	.106	1.844	2,432.987	3.050	.000	.000	.000	.000	.000	.022	31.018	.259	8.860
1979	9	.400	.000	.000	.027	.349	2,105.853	.063	.000	.000	.000	.000	.000	.006	5.633	.152	18.428
1979	1	9.453	.000	.000	.941	16.056	1,763.180	10.478	.000	.000	.005	.000	.006	.206	187.956	.946	99.261
1980	36	.000	.000	.000	.002	.012	47.737	.028	.000	.000	.000	.000	.000	.000	1.044	.002	.095
1980	18	.000	.000	.000	.001	.010	2.424	.030	.000	.000	.000	.004	.000	.000	.459	.010	.564
1980	9	.003	.001	.001	.012	.051	96.142	.160	.000	.000	.000	.000	.000	.002	6.255	.010	.134
1980	1	.000	.000	.000	.000	.000	.003	.000	.000	.000	.001	.000	.000	.000	.019	.000	.628
1981	36	.004	.000	.000	.000	.002	25.507	.012	.000	.000	.000	.000	.000	.000	.989	.008	3.377
1981	18	.508	.002	.001	.000	.023	89.697	.518	.001	.000	.000	.001	.000	.000	26.335	.128	2.236
1981	9	1.323	.003	.002	.000	.028	617.997	1.849	.000	.000	.000	.002	.000	.000	56.641	.235	5.030
1981	1	.000	.000	.000	.000	.000	91.193	.000	.001	.000	.001	.000	.000	.000	.029	.000	4.485
1982	36	1,205.667	.010	.007	.002	.131	482.042	5.323	.000	.006	.000	.009	.002	.006	58.364	.500	93.647
1982	18	1,392.915	.004	.003	.000	259.207	213.182	267.833	.000	.000	.000	.007	.000	.000	9.647	.589	102.015
1982	9	6,105.988	.003	.002	.011	.730	457.417	1.371	.000	.000	.000	.005	.000	.003	6.360	.598	143.579
1982	1	2.659	.000	.000	.000	.025	27.478	.514	.000	.000	.018	.000	.025	.000	.004	5.939	73.419

[1]A value of 150.0 given for a parameter would mean that a 10-percent error in the given parameter results in an increase of 150.0 in the residual variance.

A method of varying SMAV, which in turn limits the quantity of water that can infiltrate, was more effective. By varying SMAV, the quantity of infiltration during snowmelt varied, reflecting a more realistic simulation of freezing and thawing of the soil. Although this method produced better results, the values of SMAV were estimated values and may not represent real values of SMAV. SMAX, which put an upper limit to SMAV, was found to be very sensitive and reflects the importance of infiltration processes. A component of the model is needed to describe freezing and thawing soils and their relationship to infiltration. However, little research is devoted to this topic, and few methods of analysis are available.

The model has been calibrated reasonably well for snowmelt runoff, but more model calibration would be useful. The model simulations did not use a newly added option of reservoir storage. The main stems of Hay Creek and West Branch Antelope Creek flow through numerous stock-dam type reservoirs and section-line roads that have varying numbers and conditions of culverts, bridges, and embankments. This type of complex water routing is common in North Dakota and needs to be included in a calibrated model.

The model still needs to be calibrated for summertime low flows or rainfall-runoff conditions. To adequately calibrate a model for these conditions, more data need to be collected.

A stream-gaging station is located approximately in the middle of each watershed. The part of each watershed upstream from the stream-gaging station has some unique hydrologic characteristics apart from the part downstream. By calibrating the model for the upstream part of the watershed, a better calibrated model for the complete watershed and a better understanding of the variation in parameter values should be obtained.

Further study is needed to see how well the calibrated model can be transferred to other uninstrumented watersheds. One way of doing this is by using nearby meteorological data collected by the National Weather Service as model input for the calibrated watersheds. The results from these model simulations then could be compared to both measured runoff and the model-simulated runoff determined on the basis of data collected in the watershed. Another way is by using nearby meteorological data collected by the National Weather Service or by this study as model input for simulations of gaged watersheds in the vicinity.

The single biggest error-producing element of the modeling system is accurately defining the quantity and distribution of snow cover. Using gage catch for determining snow cover is useful only in determining the time and relative quantity of snowfall. The parameter DSCOR is a snow correction factor for daily precipitation at precipitation gages. DSCOR was designed to correct for gage-catch efficiency and variation in elevation. For the study areas, DSCOR was used to account for the snow distribution that was determined by snow surveys. DSCOR is quite sensitive, varying from 0.92 to 3.71 in the simulations, a very large range if the values had to be estimated.

SUMMARY

The study defines and analyzes the major hydrologic processes and the factors that affect them for two watersheds--the Hay Creek watershed near Wibaux, Mont., and the West Branch Antelope Creek watershed near Beulah, N. Dak. Hay Creek and West Branch Antelope Creek are ephemeral streams; most of the flow occurs during snowmelt. Of the total number of annual peaks, 2 were caused by rainfall runoff and 15 were caused by snowmelt runoff. For most antecedent conditions, rainfall-simulation studies showed that more than 1.00 in. of rainfall in 60 minutes is needed to produce runoff.

Suspended-sediment concentrations for snowmelt runoff varied from 4 to 231 mg/L for the Hay Creek watershed and from 9 to 325 mg/L for the West Branch Antelope Creek watershed. Very little rainfall runoff occurred; therefore, sediment concentrations from rainfall simulations conducted near the West Branch Antelope Creek watershed were examined. Maximum sediment concentrations from rainfall simulations were about 2,350 mg/L.

The surface-water chemical analyses generally show that for stream-gaging station 06336510 along Hay Creek, the dominant constituents are calcium, bicarbonate, and sulfate. For stream-gaging station 06336515 along Hay Creek, the dominant constituents are magnesium and sulfate. For stream-gaging station 06340524 along West Branch Antelope Creek, the dominant constituents are calcium, magnesium, and bicarbonate. For stream-gaging station 06340528 along West Branch Antelope Creek, the dominant constituents are calcium, magnesium, bicarbonate, and sulfate.

The watershed model used to simulate the Hay Creek and West Branch Antelope Creek hydrologic systems is the Precipitation-Runoff Modeling System developed by Leavesley and others (1983). Because runoff in North Dakota is caused mainly by snowmelt and because little rainfall runoff occurred, the model was calibrated for only the snowmelt period. Temporal and spatial variations of watershed climatic and hydrologic characteristics were accounted for by partitioning the watersheds into HRU's (hydrologic-response units). Testing of several partitioning schemes for the West Branch Antelope Creek watershed showed that 36 HRU's generally produced better results than 1, 9, or 18 HRU's. Partitioning of these two watersheds depended on how well the variation in the snow distribution was defined. From sensitivity analysis, parameters BST, DENMX, DSCOR, EAIR, FWCAP, SMAX, and SRX contribute the most to prediction error. BST is the base temperature above which all precipitation is rain and below which all precipitation is snow. DENMX is the average maximum snowpack density. DSCOR is the precipitation correction factor for snow. EAIR is the emissivity of the air for longwave radiation on days without precipitation. FWCAP is the free-water-holding capacity of the snowpack. SMAX is the maximum available water-holding capacity of soil profile. SRX is the maximum daily snowmelt-infiltration capacity of soil profile at field capacity. The values for BST, DENMX, FWCAP, and SRX were fairly constant during optimization. Therefore, the most critical values to determine are those for DSCOR, EAIR, and SMAX.

SELECTED REFERENCES

Chow, Ven Te, 1959, Open-channel hydraulics: New York, McGraw-Hill Book Co., 680 p.

Colbeck, S.C., 1980, Dynamics of snow and ice masses: New York, Academic Press, 468 p.

Crawley, M.E., and Emerson, D.G., 1981, Hydrologic characteristics and possible effects of surface mining in the northwestern part of West Branch Antelope Creek basin, Mercer County, North Dakota: U.S. Geological Survey Water-Resources Investigations 81-79, 73 p.

Crosby, O.A., 1975, Magnitude and frequency of floods from small drainage basins in North Dakota: U.S. Geological Survey Water-Resources Investigations 19-75, 24 p.

Dawdy, D.R., Lichty, R.W., and Bergmann, J.M., 1972, A rainfall-runoff simulation model for estimation of flood peaks for small drainage basins: U.S. Geological Survey Professional Paper 506-B, 28 p.

Dawdy, D.R., and O'Donnell, Terence, 1965, Mathematical models of catchment behavior: Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division, v. 91, no. HY4, p. 123-137.

Dawdy, D.R., Schaake, J.C., and Alley, W.M., 1978, User's guide for distributed routing rainfall-runoff model: U.S. Geological Survey Water-Resources Investigations 78-90, 151 p.

Eagleson, P.S., 1970, Dynamic hydrology: New York, McGraw-Hill Book Co., 462 p.

Emerson, D.G., 1982, Hydrologic analysis of high flow from snowmelt on small basins in the Fort Union coal region: Proceedings of North Dakota Academy of Science 74th Annual Meeting, Bismarck, N. Dak., April 22-24, 1982, v. 36, p. 42.

Emerson, D.G., Norbeck, S.W., and Boespflug, K.L., 1983, Data from the surface-water hydrologic investigations of the Hay Creek study area, Montana, and the West Branch Antelope Creek study area, North Dakota, October 1976 through April 1982: U.S. Geological Survey Open-File Report 83-136, 273 p.

Granger, R.J., 1977, Energy exchange during melt of a prairie snow cover: University of Saskatchewan, unpublished M.S. thesis, 122 p.

Granger, R.J., and Male, D.H., 1978, Melting of a prairie snowpack: Journal of Applied Meteorology, v. 17, no. 12, p. 1833-1842.

Gray, D.M., and O'Neill, A.D.J., 1974, Application of the energy budget for predicting snowmelt runoff, *in* Santaford, H.S., and Smith, J.L., eds., Advanced concepts and techniques in the study of snow and ice resources: Washington, D.C., U.S. National Academy of Sciences, p. 108-118.

Hem, J.D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Henderson, F.M., 1966, Open-channel flow: New York, MacMillan Publishing Company, Inc., 522 p.

Hines, W.G., Rickert, D.A., McKenzie, S.W., and Bennett, J.P., 1975, Formulation and use of practical models for river-quality assessment: U.S. Geological Survey Circular 715-B, 13 p.

Horak, W.F., 1983, Hydrology of the Wibaux-Beach lignite deposit area, eastern Montana and western North Dakota: U.S. Geological Survey Water-Resources Investigations Report 83-4157, 89 p.

Jensen, M.E., and Haise, H.R., 1963, Estimating evapotranspiration from solar radiation: Proceedings of the American Society of Civil Engineers, Journal of the Irrigation and Drainage Division, v. 89, no. IR4, p. 15-41.

Kane, D.L., 1981, Snowmelt infiltration and runoff on frozen ground: Fairbanks, University of Alaska, Institute of Water Resources Report 80-06, 23 p.

Leavesley, G.H., 1973, A mountain watershed simulation model: Fort Collins, Colorado State University, Ph.D. dissertation, 175 p.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system--User's manual: U.S. Geological Survey Water-Resources Investigations Report 83-4238, 207 p.

Linsley, R.K., Kohler, M.A., and Paulhus, J.L., 1949, Applied hydrology: New York, McGraw-Hill Book Co., 482 p.

Male, D.H., and Granger, R.J., 1978, Energy mass fluxes at the snow surface in a prairie environment, *in* Colbeck, S.C., and Ray, M., eds., Modeling of snow cover runoff, Hanover, New Hampshire, 1978, Proceedings: U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, p. 101-124.

Miller, J.E., and Frink, D.L., 1982, Changes in flood response of the Red River of the North basin, North Dakota-Minnesota: U.S. Geological Survey Open-File Report 82-774, 158 p.

Peck, E.L., 1974, Effect of snow cover on upward movement of soil moisture: Proceedings of the American Society of Civil Engineers, Journal of the Irrigation and Drainage Division, v. 100, no. IR4, December 1974, p. 405-412.

Plummer, L.N., Blair, F.J., and Truesdell, A.H., 1976, WATEQF: A FORTRAN IV version of WATEQ, a computer program for calculating chemical equilibrium of natural waters: U.S. Geological Survey Water-Resources Investigations 76-13, 63 p.

Riley, J.P., Israelsen, E.K., and Eggleston, K.O., 1973, Some approaches to snowmelt prediction, *in* The role of snow and ice in hydrology: International Association of Hydrological Sciences, no. 107, p. 956-971.

Rosenbrock, H.H., 1960, An automatic method of finding the greatest or least value of a function: Computer Journal, v. 3, p. 175-184.

Steppuhn, Harold, 1976, Areal water equivalents for prairie snow cover by centralized sampling: Western Snow Conference, Calgary, Alberta, 1976, p. 63-68.

Steppuhn, Harold, and Dyck, G.E., 1974, Estimating true basin snow cover, *in* Santaford, H.S., and Smith, J.L., eds., Advanced concepts and techniques in the study of snow and ice resources: Washington, D.C., U.S. National Academy of Sciences, p. 314-324.

U.S. Army Corps of Engineers, 1956, Snow hydrology--Summary report of the snow investigations: Portland, Oregon, North Pacific Division, 437 p.

U.S. Department of Agriculture, Soil Conservation Service, 1958, Soil survey of Wibaux County, Montana: 43 p.

____1978, Soil survey of Mercer County, North Dakota: 223 p.

U.S. Department of the Interior, 1977, Resource and potential reclamation evaluation: Beulah Trench EMRIA Report 10, 1977, 74 p.

U.S. Office of Surface Mining Reclamation and Enforcement, 1977, Surface mining reclamation and enforcement provisions: Federal Register, v. 42, no. 239, Tuesday, December 13, 1977, part III, p. 62641-62661.

U.S. Weather Bureau, 1961, Rainfall frequency atlas of the United States: U.S. Weather Bureau Technical Paper 40, 115 p.

Velz, C.J., 1970, Applied stream sanitation: New York, Wiley-Interscience, 619 p.

Weeks, J.B., Leavesley, G.H., Welder, F.A., and Saulner, G.J., Jr., 1974, Simulated effects of oil-shale development on the hydrology of Piceance basin, Colorado: U.S. Geological Survey Professional Paper 908, 83 p.

SUPPLEMENTAL INFORMATION

Energy budget for a snowpack

The ablation of a snowpack--that is, the decrease of its snow water equivalent--is controlled by the processes of snowmelt, evaporation, and condensation; the flow of water within the snowpack; and the infiltration of water into the ground. The rate of snowmelt is determined by the various heat-transfer processes. The energy balance of a snowpack as described by Granger and Male (1978) can be written as

$$Q_t = Q_n + Q_h + Q_e + Q_g + Q_m + Q_r, \qquad (2)$$

where

Q_t = the energy stored within the snowpack, in langleys;
Q_n = the net all-wave radiation, in langleys;
Q_h = the convective or sensible heat, in langleys;
Q_e = the turbulent transfer of latent heat, in langleys;
Q_g = the heat transfer by conduction from soil, in langleys;
Q_m = the energy associated with melt water, in langleys; and
Q_r = the latent energy associated with rain, in langleys.

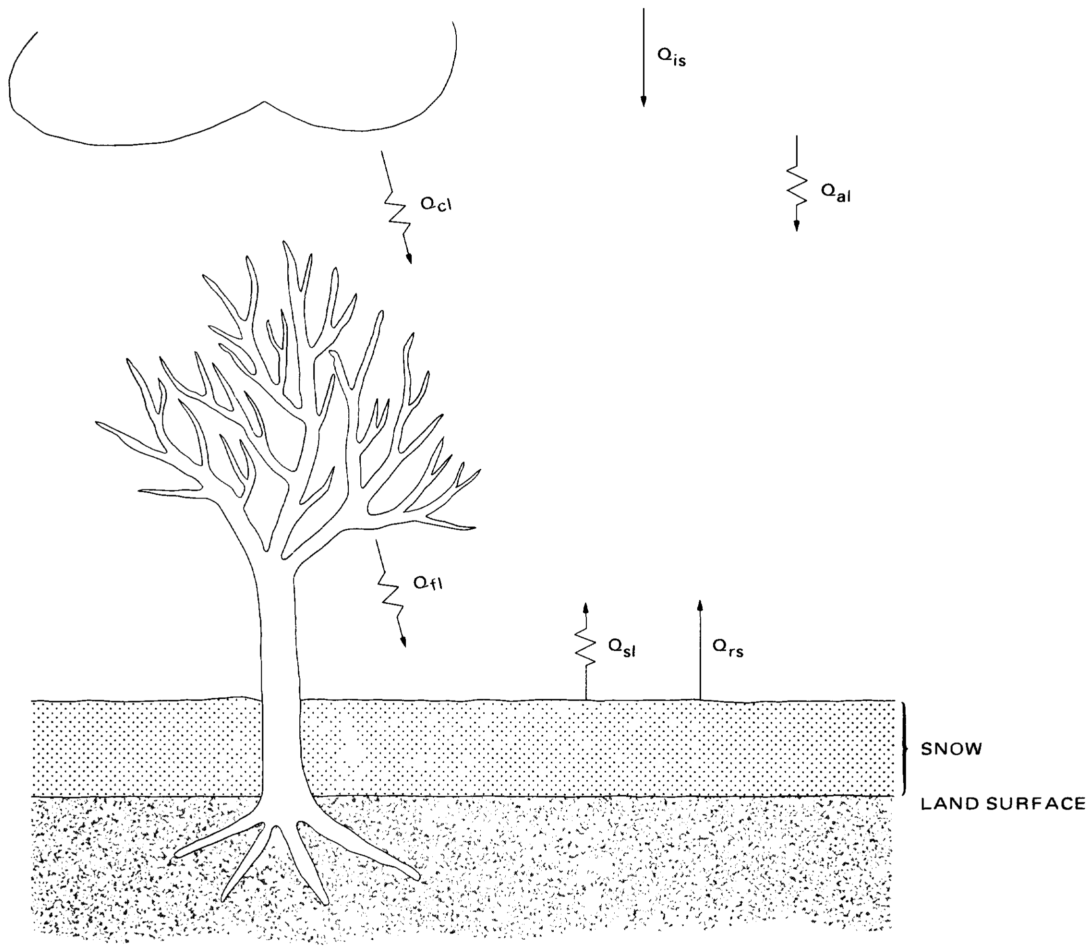
The net radiation (fig. 26) consists of incoming shortwave (global) radiation (Q_{is}); reflective shortwave radiation due to the snowpack (Q_{rs}); longwave (terrestrial) radiation from the cloud cover (Q_{cl}), atmosphere (Q_{al}), and forest canopy (Q_{fl}); and longwave radiation emitted from the snowpack (Q_{sl}). Net radiation can be expressed by

$$Q_n = Q_{is} - Q_{rs} + Q_{cl} + Q_{al} + Q_{fl} - Q_{sl}, \qquad (3)$$

where all variables are as previously defined.

The incoming shortwave radiation is the major daytime heat input. Cumulative shortwave-radiation curves for the two study areas and for Bismarck, N. Dak., are shown in figure 27. The Bismarck station is located at a latitude of 46°46' and should receive greater shortwave radiation than the Hay Creek station located at a latitude of 47°00'. The West Branch Antelope Creek station is located at a latitude of 47°21' and should receive the least shortwave radiation. The cumulative shortwave-radiation curves for the winter of 1978-79 (fig. 27) are just the opposite from that expected. The cumulative shortwave-radiation curves for the winter of 1979-80 (fig. 27) show little variation from November through February and good agreement for March and April. The cumulative shortwave-radiation curves for the winter of 1980-81 (fig. 27) show good agreement for the entire winter. These curves indicate the magnitude, variation, and error expected if shortwave radiation is extrapolated for use in snowmelt analysis.

The shortwave radiation is most critical just before and during the melt period. The daily incoming shortwave radiation for the three locations is shown in figure 28. The daily shortwave radiation for each location follows the same general trend. The shortwave radiation varies for some days but the differences cancel out even after a short period resulting in a reasonably good fit.



EXPLANATION

Q_{is} INCOMING SHORTWAVE (GLOBAL) RADIATION

Q_{rs} REFLECTIVE SHORTWAVE RADIATION DUE TO THE SNOWPACK

Q_{cl} LONGWAVE RADIATION FROM THE CLOUD COVER

Q_{al} LONGWAVE RADIATION FROM THE ATMOSPHERE

Q_{fl} LONGWAVE RADIATION FROM THE FOREST CANOPY

Q_{sl} LONGWAVE RADIATION EMITTED FROM THE SNOWPACK

Figure 26.—Components of net radiation (Q_n).

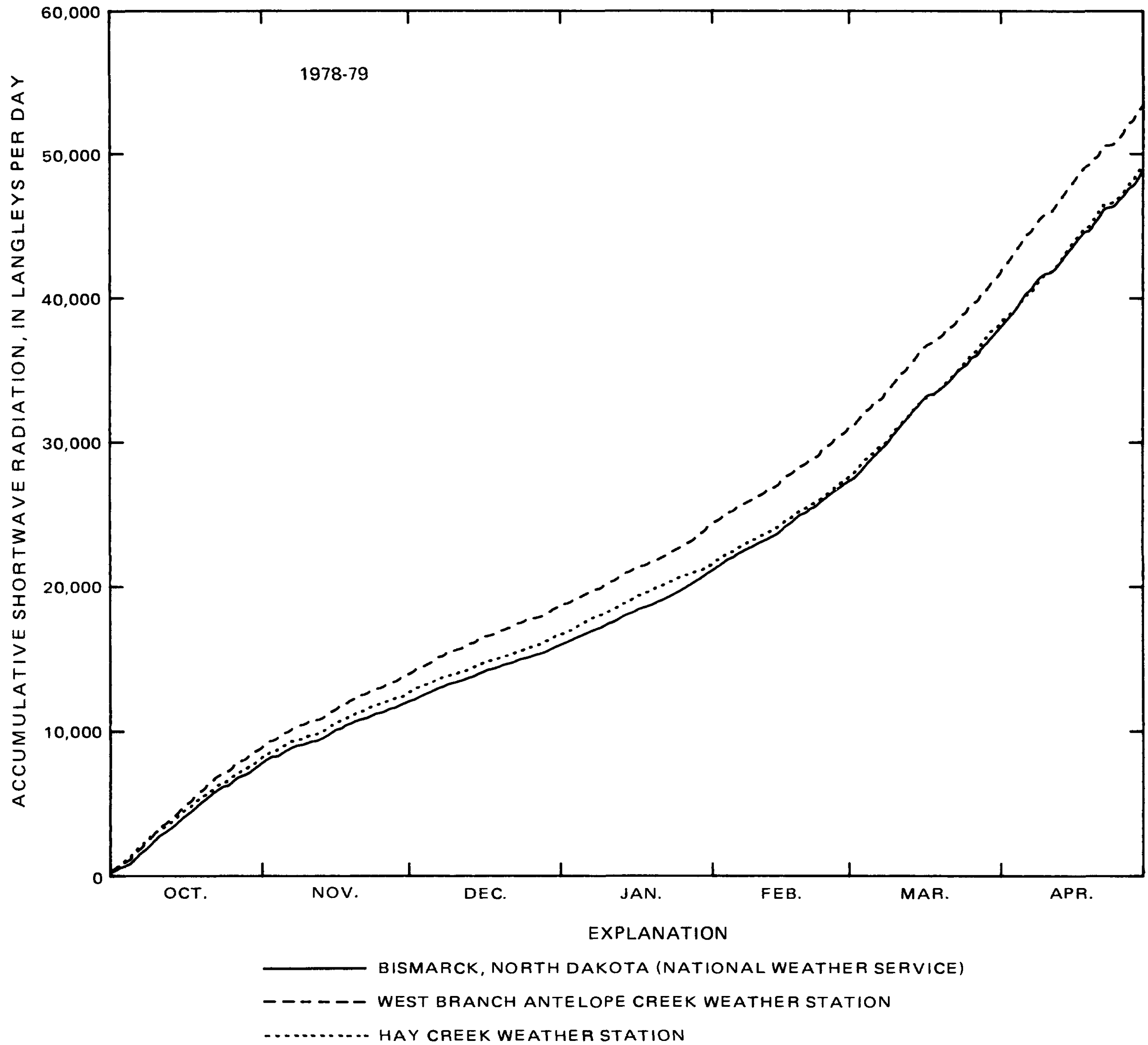


Figure 27.—Cumulative shortwave-radiation curves for the Hay Creek and West Branch Antelope Creek watersheds and Bismarck, N. Dak.

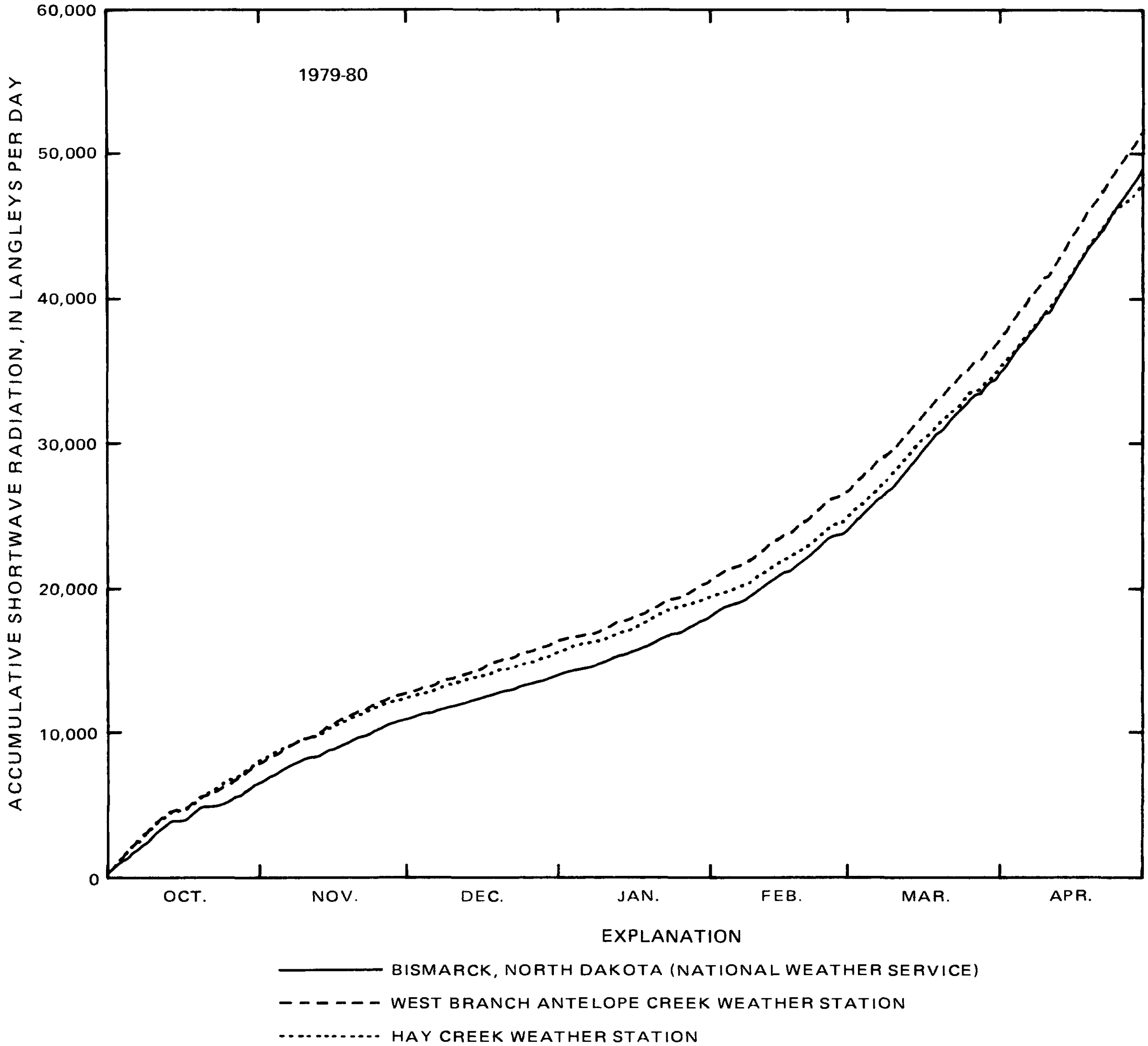


Figure 27.--Cumulative shortwave-radiation curves for the Hay Creek and West Branch Antelope Creek watersheds and Bismarck, N. Dak.--Continued.

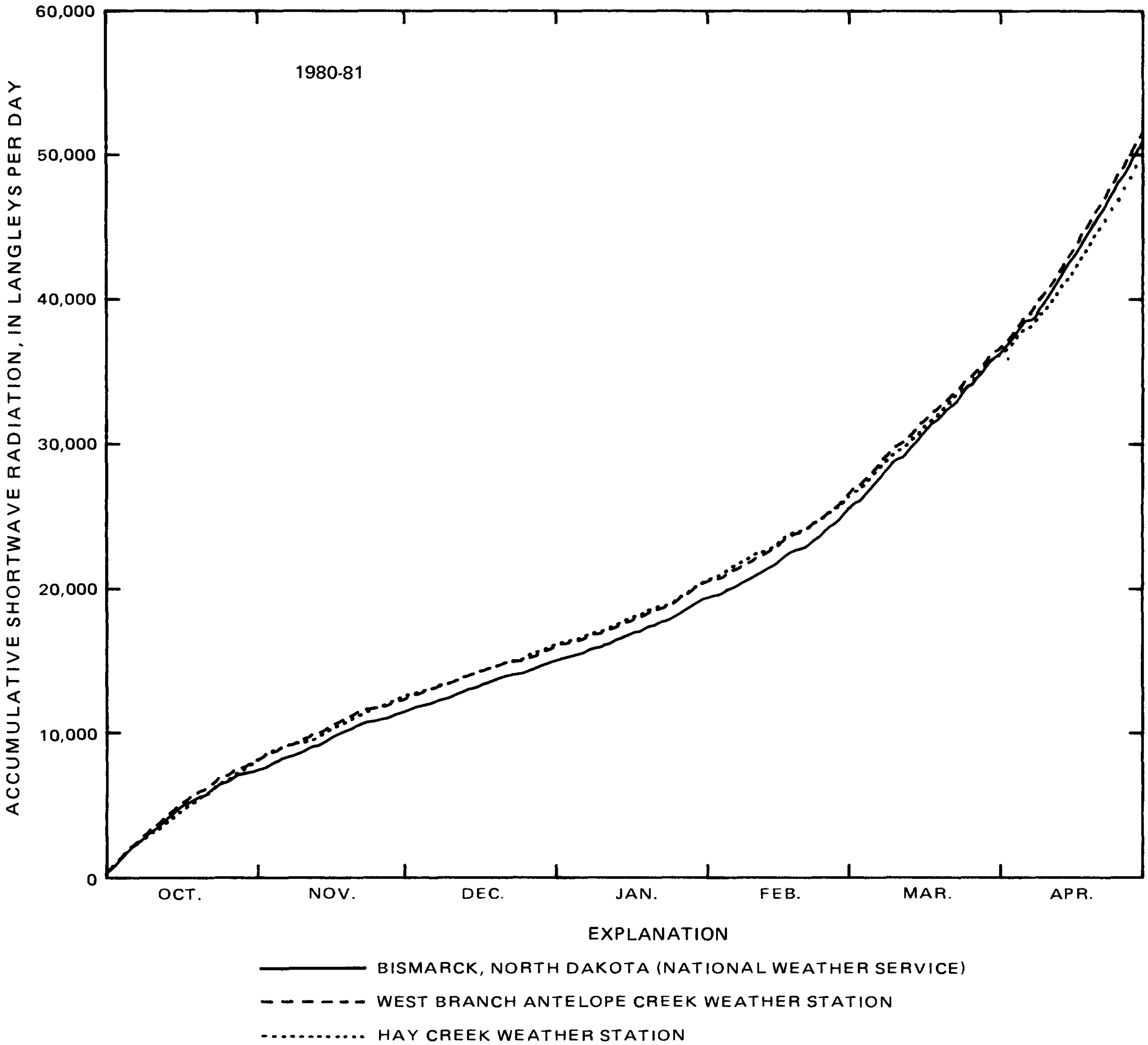


Figure 27.—Cumulative shortwave-radiation curves for the Hay Creek and West Branch Antelope Creek watersheds and Bismarck, N. Dak.--Continued.

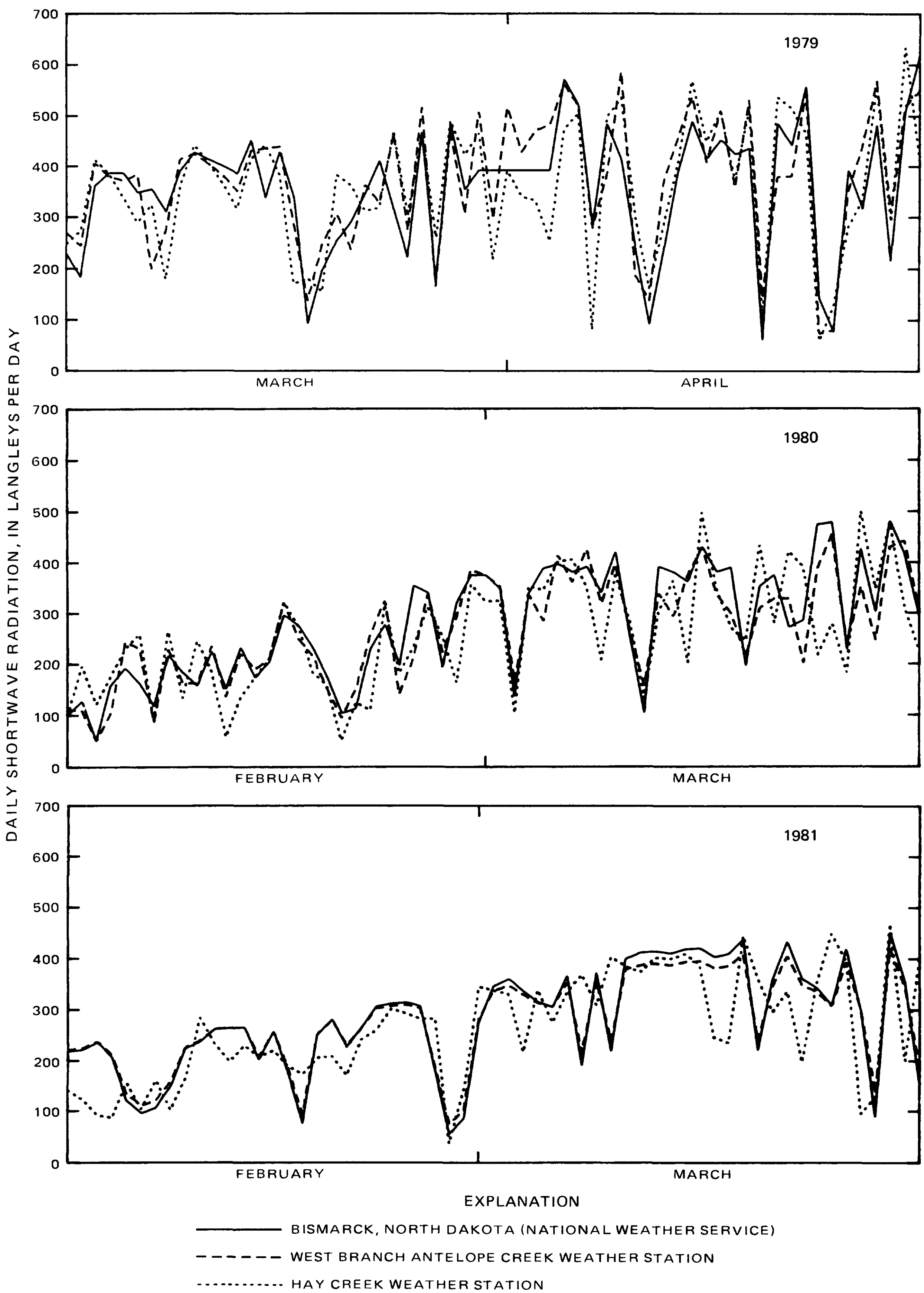


Figure 28.—Daily incoming shortwave radiation for the Hay Creek and West Branch Antelope Creek watersheds and Bismarck, N. Dak.

The net shortwave radiation (Q_{ns}) can be computed by the expression

$$Q_{ns} = \frac{(1-a)}{B} Q_{is}, \quad (4)$$

where

a = the albedo written as a decimal fraction,

B = the thermal quality of the snowpack and is assumed to be 0.97 for a melting snowpack, and

Q_{is} is as previously defined. For a shallow prairie snowpack, the albedo varies from 80 percent for fresh snow to 20 percent for melting late season snow (Colbeck, 1980, p. 356). Using an albedo of 0.40, the net shortwave radiation for the 1979 melt period was computed for the Hay Creek watershed (fig. 29). The magnitudes vary from 0 to 0.65 Ly/min.

The longwave radiation from the atmosphere for clear skies (Q_{al}) can be computed by the expression

$$Q_{al} = \sigma T_a^4 (a+b \quad e), \quad (5)$$

where

σ = the Stephan-Boltzman constant [0.814×10^{-10}(Ly/min)/°K^{-4}];

T_a = the absolute air temperature, in degrees Kelvin;

e = the vapor pressure of air, in millibars; and

a and b are empirical parameters. Equation 5 does not hold true for forested canopy (Q_{cl}) or cloudy skies (Q_{fl}).

The longwave radiation emitted from the snow surface (Q_{sl}) can be computed by the expression

$$Q_{sl} = \varepsilon \sigma T_s^4, \quad (6)$$

where

ε = the emissivity;

T_s = the absolute temperature of the snow surface, in degrees Kelvin; and

σ is as previously defined.

The incoming longwave radiation and the longwave radiation emitted by the snowpack are of the same magnitude and usually have a small net effect. Assuming clear skies and continuous snow cover during the 1979 melt period, the net longwave radiation would range from -0.16 to -0.3 Ly/min.

The turbulent transfer of latent heat (Q_e) is the energy exchange by evaporation, condensation, or sublimation from the air to the snow surface. The vapor pressure gradient and wind speed are the principal parameters

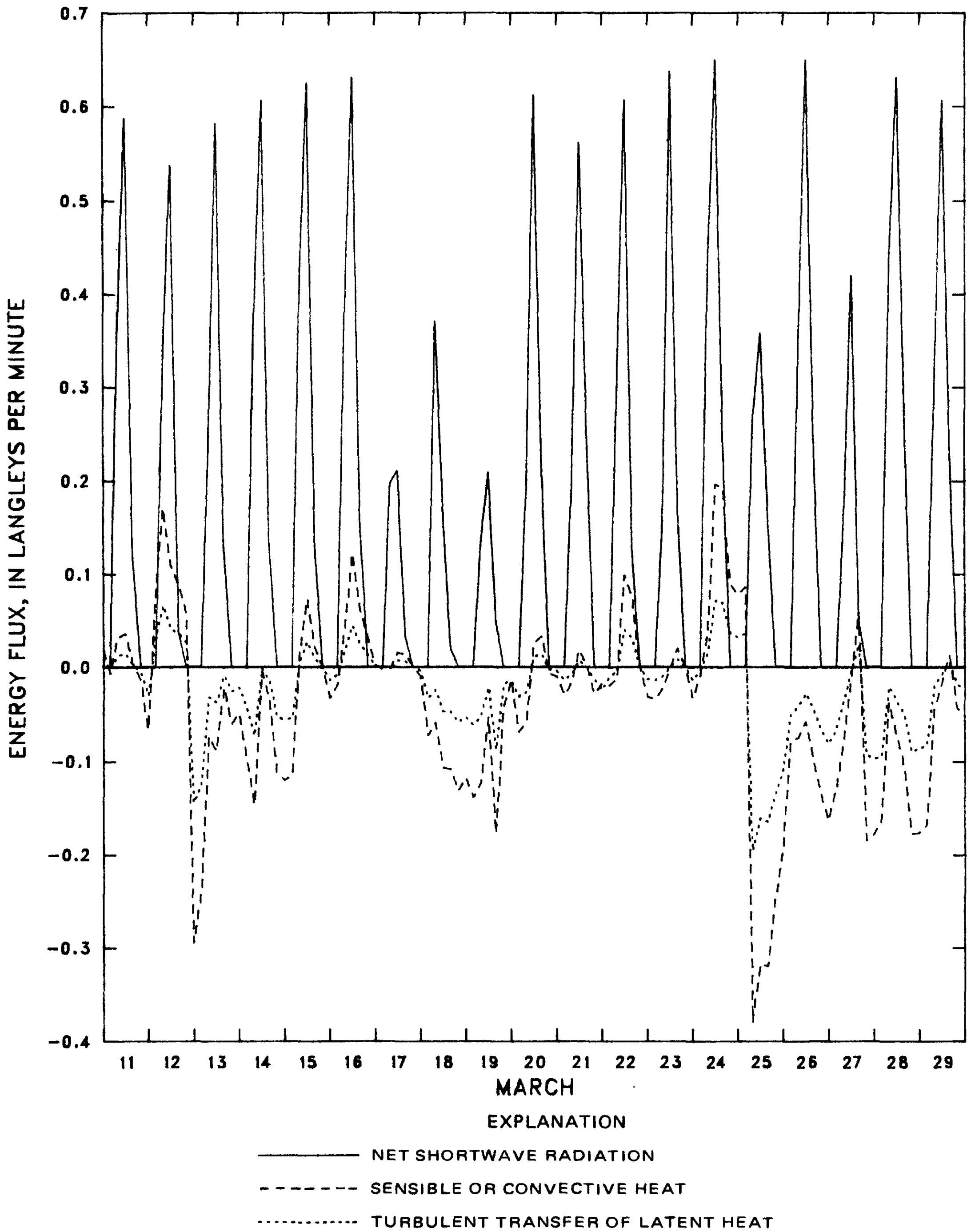


Figure 29.—Energy budget for the Hay Creek watershed, March 11-29, 1979.

affecting this process. Latent heat can be computed by the empirical relationship

$$Q_e = 53.08(z_a z_b)^{-1/6}(e_a - e_s)V, \qquad (7)$$

where

z_a = the measuring height, in feet, of air vapor pressure;
z_b = the measuring height, in feet, of wind speed;
e_a = the air vapor pressure, in millibars;
e_s = the snow vapor pressure, in millibars; and
V = the wind speed, in miles per hour.

Using a snow vapor pressure of 6.11 mb, latent heat for melt period was computed for the Hay Creek watershed (fig. 29). The magnitudes varied from -0.20 to 0.38 Ly/min. Generally, the latent heat responds to the radiation following a cycle of evaporation during the day and condensation at night damping the net daily effect.

The sensible or convective heat (Q_h) is the energy exchange from the air to the snow surface. Sensible heat can be computed by the empirical expression

$$Q_h = 0.00344\left(\frac{P}{P_o}\right)(z_c z_b)^{-1/6}(T_a - T_s)V, \qquad (8)$$

where

P = the air pressure at the site, in millibars;
P_o = the air pressure at sea level, in millibars;
z_c = the measuring height, in feet, of air temperature;
T_a = the air temperature, in degrees Fahrenheit;
T_s = the snow temperature, in degrees Fahrenheit; and

z_b and V are as previously defined. A value of 0.93 is used for P/P_o (U.S. Army Corps of Engineers, 1956, pl. 5-5, fig. 6) and 32.0 °F normally is used for snow-surface temperature. Sensible heat for the 1979 melt period was computed for the Hay Creek watershed (fig. 29) using equation 8. The magnitudes varied from -0.20 to 0.07 Ly/min.

The heat transferred to the snowpack by conduction from the soil (Q_g) generally is considered negligible. Granger (1977, p. 109-122) has measured values in the range of 0 to 1.09×10^{10} Ly/d for soils in Saskatchewan, Canada.

The heat transferred to a snowpack from rain generally is small. Because rain on snow seldom occurs in North Dakota and the effect is small, the heat flux due to rainfall is ignored.

Values computed for the various heat fluxes for a melting snowpack were determined by empirical equations. Although error is introduced with empirical equations, values for various heat fluxes could not have been determined otherwise because of the uncommon types of data needed. If each heat flux were measured directly in the field, error would be introduced by transferring that data throughout a watershed. Thus, these empirical equations are quite useful and their magnitudes are similar to those measured by Granger (1977).

For the most part, the derivation of these equations and the measurement of heat fluxes have been done for a continuous snowpack. Bare ground within the snow-cover areas significantly changes the energy balance at the land surface. Local advection from bare patches to the snow needs to be considered and becomes increasingly important as the snow cover dwindles. Gray and O'Neill (1974, p. 112) estimated that during a 6-day interval, 44 percent of the energy supplied to an isolated melting snowpack was by sensible-heat transfer. During a period of continuous snow cover, sensible heat for the same location was 7 percent of the energy supplied. Much research is needed for the melt of a discontinuous snowpack, which is very common during the melt period on the prairie.

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds

[°C, degrees Celsius; ft^3/s, cubic foot per second; µS/cm at 25°C, microsiemens per centimeter; mg/L, milligrams per liter; µg/L, micrograms per liter; JTU, Jackson turbidity unit; pCi/L, picocuries per liter]

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
Station 06336510, Hay Creek watershed										
Temperature (°C)	22	15.5	0.0	3.2	4.0	14.5	5.2	1.2	0.5	0.0
Discharge, instantaneous, stream (ft^3/s)	23	66	.09	6.3	14	57	5.1	2.0	.30	.09
Specific conductance (µS/cm at 25°C)	22	1,950	170	440	418	1,810	668	255	200	171
pH (units)	4	8.3	7.5	--	--	--	--	--	--	--
Carbon dioxide, dissolved (mg/L as CO_2)	2	4.7	3.2	--	--	--	--	--	--	--
Bicarbonate (mg/L as HCO_3)	2	100	92	--	--	--	--	--	--	--
Carbonate (mg/L as CO_3)	2	0	0	--	--	--	--	--	--	--
Nitrogen, ammonia + organic, dissolved (mg/L as N)	4	1.2	.48	--	--	--	--	--	--	--
Hardness (mg/L as $CaCO_3$)	4	440	80	--	--	--	--	--	--	--
Calcium, dissolved (mg/L as Ca)	4	100	25	--	--	--	--	--	--	--
Magnesium, dissolved (mg/L as Mg)	4	47	4.2	--	--	--	--	--	--	--
Sodium, dissolved (mg/L as Na)	4	34	.3	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
Station 06336510, Hay Creek watershed, Continued										
Sodium-adsorption ratio	4	0.7	0.0	--	--	--	--	--	--	--
Percent sodium	4	14	1	--	--	--	--	--	--	--
Potassium, dissolved (mg/L as K)	4	11	8.8	--	--	--	--	--	--	--
Chloride, dissolved (mg/L as Cl)	4	2.7	1.4	--	--	--	--	--	--	--
Sulfate, dissolved (mg/L as SO_4)	4	360	10	--	--	--	--	--	--	--
Fluoride, dissolved (mg/L as F)	4	.1	.1	--	--	--	--	--	--	--
Silica, dissolved (mg/L as SiO_2)	4	13	7.0	--	--	--	--	--	--	--
Boron, dissolved (µg/L as B)	4	260	50	--	--	--	--	--	--	--
Iron, dissolved (µg/L as Fe)	4	90	60	--	--	--	--	--	--	--
Manganese, dissolved (µg/L as Mn)	4	70	20	--	--	--	--	--	--	--
Molybdenum, dissolved (µg/L as Mo)	4	10	0	--	--	--	--	--	--	--
Strontium, dissolved (µg/L as Sr)	4	410	80	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
	Station 06336510, Hay Creek watershed, Continued									
Aluminum, dissolved (μg/L as Al)	2	60	30	--	--	--	--	--	--	--
Dissolved solids, sum of constituents (mg/L)	4	671	105	--	--	--	--	--	--	--
Dissolved solids (tons per day)	2	.33	.16	--	--	--	--	--	--	--
Dissolved solids (tons per acre-foot)	4	.91	.14	--	--	--	--	--	--	--
Alkalinity, laboratory (mg/L as $CaCO_3$)	4	170	75	--	--	--	--	--	--	--
Noncarbonate hardness (mg/L as $CaCO_3$)	4	270	4	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
				Station 06336515, Hay Creek watershed						
Temperature (°C)	81	25.0	0.0	6.0	7.1	21.8	10.0	2.0	0.5	0.0
Discharge, instantaneous, stream (ft^3/s)	82	76	.00	4.3	10	23	3.4	.48	.04	.01
Specific conductance (µS/cm at 25°C)	82	3,050	180	1,630	784	2,840	2,310	1,600	919	346
pH (units)	13	8.4	6.3	7.5	.6	8.4	8.0	7.5	7.3	6.3
Carbon dioxide, dissolved (mg/L as CO_2)	3	12	3.6	--	--	--	--	--	--	--
Bicarbonate (mg/L as HCO_3)	3	150	120	--	--	--	--	--	--	--
Carbonate (mg/L as CO_3)	3	0	0	--	--	--	--	--	--	--
Nitrogen, ammonia + organic, dissolved (mg/L as N)	9	1.6	.71	1.2	.31	1.6	1.4	1.1	.90	.71
Hardness (mg/L as $CaCO_3$)	13	1,600	220	700	480	1,600	1,200	500	300	220
Calcium, dissolved (mg/L as Ca)	13	230	44	110	61	230	170	79	54	44
Magnesium, dissolved (mg/L as Mg)	13	240	26	110	80	240	180	69	38	26
Sodium, dissolved (mg/L as Na)	13	200	19	95	71	200	180	76	32	19
Sodium adsorption ratio	13	2.5	.6	1.5	.7	2.5	2.2	1.4	.8	.6
Percent sodium	13	25	15	21	3	25	24	22	18	15

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
	Station 06336515, Hay Creek watershed, Continued									
Potassium, dissolved (mg/L as K)	13	15	7.7	11	2.5	15	14	10	9.5	7.7
Chloride, dissolved (mg/L as Cl)	13	30	3.8	12	7.8	30	17	9.2	6.0	3.8
Sulfate, dissolved (mg/L as SO_4)	13	1,600	140	680	540	1,600	1,200	450	230	140
Fluoride, dissolved (mg/L as F)	13	.5	.1	.2	.1	.5	.2	.1	.1	.1
Silica, dissolved (mg/L as SiO_2)	13	12	1.2	7.7	2.6	12	9.2	7.6	6.4	1.2
Boron, dissolved (µg/L as B)	13	880	160	380	230	880	580	350	170	160
Iron, dissolved (µg/L as Fe)	13	440	60	200	120	440	310	160	100	60
Manganese, dissolved (µg/L as Mn)	12	370	40	170	100	370	230	150	79	40
Molybdenum, dissolved (µg/L as Mo)	13	10	0	4	5	10	10	1	0	0
Strontium, dissolved (µg/L as Sr)	13	1,700	220	790	540	1,700	1,400	600	320	220
Aluminum, dissolved (µg/L as Al)	2	10	10	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics: Number of samples	Maximum	Minimum	Mean	Standard deviation	Percent of samples in which values were less than or equal to those shown: 95	75	50	25	5
				Station 06336515, Hay Creek watershed, Continued						
Lithium, dissolved (μg/L as Li)	4	20	10	--	--	--	--	--	--	--
Dissolved solids, sum of constituents (mg/L)	13	2,500	312	1,150	805	2,500	1,970	825	448	312
Dissolved solids (tons per day)	13	22.4	.04	5.56	7.19	22.4	10.5	1.09	.28	.04
Dissolved solids (tons per acre-foot)	13	3.40	.42	1.56	1.09	3.40	2.68	1.12	.61	.42
Alkalinity, laboratory (mg/L as $CaCO_3$)	13	430	86	210	110	430	300	180	120	86
Noncarbonate hardness (mg/L as $CaCO_3$)	13	1,200	120	490	390	1,200	900	320	180	120

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
Station 06340524, West Branch Antelope Creek watershed										
Temperature (°C)	48	21.0	0.0	6.1	5.5	17.6	10.0	4.8	1.6	0.0
Discharge, instantaneous, stream (ft^3/s)	45	79	.01	9.0	19	70	6.3	1.6	.11	.01
Turbidity (JTU)	2	190	65	--	--	--	--	--	--	--
Color (Platinum-cobalt units)	1	550	550	--	--	--	--	--	--	--
Specific conductance (µS/cm at 25°C)	43	900	75	277	200	734	360	215	120	80
pH (units)	8	7.9	6.6	7.1	.4	7.9	7.3	7.1	6.7	6.6
Carbon dioxide, dissolved (mg/L as CO_2)	3	16	4.2	--	--	--	--	--	--	--
Bicarbonate (mg/L as HCO_3)	3	72	42	--	--	--	--	--	--	--
Carbonate (mg/L as CO_3)	3	0	0	--	--	--	--	--	--	--
Nitrogen, organic, dissolved (mg/L as N)	1	.87	.87	--	--	--	--	--	--	--
Nitrogen, ammonia, dissolved (mg/L as N)	1	.06	.06	--	--	--	--	--	--	--
Nitrogen, ammonia + organic, dissolved (mg/L as N)	7	3.2	.70	1.6	.95	3.2	2.5	.98	.93	.70
Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	1	.30	.30	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
	Station 06340524, West Branch Antelope Creek watershed, Continued									
Phosphorous, dissolved (mg/L as P)	1	0.60	0.60	--	--	--	--	--	--	--
Carbon, organic, dissolved (mg/L as C)	1	21	21	--	--	--	--	--	--	--
Hardness (mg/L as $CaCO_3$)	8	120	24	65	35	120	99	59	33	24
Calcium, dissolved (mg/L as Ca)	8	24	5.6	14	7.1	24	22	13	7.4	5.6
Sodium adsorption ratio	8	.2	.1	.2	.0	.2	.2	.2	.1	.1
Percent sodium	8	9	3	7	2	9	8	8	6	3
Potassium, dissolved (mg/L as K)	8	15	4.9	10	3.5	15	13	10	6.8	4.9
Chloride, dissolved (mg/L as Cl)	8	17	1.3	6.1	6.5	17	13	3.4	1.6	1.3
Sulfate, dissolved (mg/L as SO_4)	8	50	4.8	20	17	50	35	14	5.7	4.8
Fluoride, dissolved (mg/L as F)	8	.1	.0	.1	.0	.1	.1	.1	.1	.0
Silica, dissolved (mg/L as SiO_2)	8	12	3.9	8.1	2.8	12	11	8.2	5.6	3.9
Arsenic, dissolved (µg/L as As)	1	3	3	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
	Station 06340524, West Branch Antelope Creek watershed, Continued									
Barium, dissolved (μg/L as Ba)	1	0	0	--	--	--	--	--	--	--
Beryllium, dissolved (μg/L as Be)	1	0	0	--	--	--	--	--	--	--
Boron, dissolved (μg/L as B)	8	190	50	100	50	190	150	100	60	50
Cadmium, dissolved (μg/L as Cd)	1	0	0	--	--	--	--	--	--	--
Chromium, dissolved (μg/L as Cr)	1	0	0	--	--	--	--	--	--	--
Cobalt, dissolved (μg/L as Co)	1	0	0	--	--	--	--	--	--	--
Copper, dissolved (μg/L as Cu)	1	11	11	--	--	--	--	--	--	--
Iron, dissolved (μg/L as Fe)	8	400	110	180	100	400	210	140	110	110
Lead, dissolved (μg/L as Pb)	1	5	5	--	--	--	--	--	--	--
Manganese, dissolved (μg/L as Mn)	8	60	10	24	17	60	30	20	10	10
Molybdenum, dissolved (μg/L as Mo)	8	10	0	5	5	10	10	6	1	0
Nickel, dissolved (μg/L as Ni)	1	4	4	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
Station 06340524, West Branch Antelope Creek watershed, Continued										
Strontium, dissolved (μg/L as Sr)	8	90	20	70	30	90	90	80	40	20
Vanadium, dissolved (μg/L as V)	1	3.0	3.0	--	--	--	--	--	--	--
Zinc, dissolved (μg/L as Zn)	1	10	10	--	--	--	--	--	--	--
Aluminum, dissolved (μg/L as Al)	3	200	40	--	--	--	--	--	--	--
Lithium, dissolved (μg/L as Li)	2	10	0	--	--	--	--	--	--	--
Selenium, dissolved (μg/L as Se)	1	1	1	--	--	--	--	--	--	--
Dissolved solids, residue at 180°C (mg/L)	1	134	134	--	--	--	--	--	--	--
Dissolved solids, sum of constituents (mg/L)	8	160	34	99	45	160	146	102	60	34
Dissolved solids (tons per day)	5	1.84	.09	.98	.69	1.84	1.66	.85	.38	.09
Dissolved solids (tons per acre-foot)	8	.22	.05	.14	.06	.22	.21	.14	.78	.05
Nitrogen, ammonia, dissolved (mg/L as NH_4)	1	.08	.08	--	--	--	--	--	--	--
Mercury, dissolved (μg/L as Hg)	1	.0	.0	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
Station 06340524, West Branch Antelope Creek watershed, Continued										
Alkalinity, laboratory (mg/L as $CaCO_3$)	8	81	16	50	21	81	68	49	35	16
Noncarbonate hardness (mg/L as $CaCO_3$)	8	51	0	16	17	51	25	10	5	0
Potassium 40, dissolved (pCi/L as K^{40})	1	9.7	9.7	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
Station 06340528, West Branch Antelope Creek watershed										
Temperature (°C)	72	21.0	0.0	5.6	6.8	20.5	9.2	2.0	1.0	0.0
Discharge, instantaneous, stream (ft^3/s)	58	140	.01	12	27	85	11	2.1	.49	.02
Turbidity (JTU)	2	85	85	--	--	--	--	--	--	--
Color (Platinum-cobalt units)	1	70	70	--	--	--	--	--	--	--
Specific conductance (µS/cm at 25°C)	58	1,400	65	467	376	1,300	785	315	185	89
pH (units)	12	8.1	7.0	7.5	.3	8.1	7.7	7.4	7.3	7.0
Carbon dioxide, dissolved (mg/L as CO_2)	3	9.4	5.2	--	--	--	--	--	--	--
Bicarbonate (mg/L as HCO_3)	3	150	74	--	--	--	--	--	--	--
Carbonate (mg/L as CO_3)	3	0	0	--	--	--	--	--	--	--
Nitrogen, organic, dissolved (mg/L as N)	1	.40	.40	--	--	--	--	--	--	--
Nitrogen, ammonia, dissolved (mg/L as N)	1	.01	.01	--	--	--	--	--	--	--
Nitrogen, ammonia + organic, dissolved (mg/L as N)	8	12	.41	2.3	4.0	12	1.2	.98	.54	.41
Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	1	.21	.21	--	--	--	--	--	--	--

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
	Station 06340528, West Branch Antelope Creek watershed, Continued									
Phosphorous, dissolved (mg/L as P)	1	0.10	0.10	--	--	--	--	--	--	--
Carbon, organic, dissolved (mg/L as C)	1	9.5	9.5	--	--	--	--	--	--	--
Hardness (mg/L as $CaCO_3$)	10	530	32	170	160	530	260	92	59	32
Calcium, dissolved (mg/L as Ca)	10	130	7.9	39	38	130	56	21	13	7.9
Magnesium, dissolved (mg/L as Mg)	10	50	2.9	18	16	50	30	9.4	6.5	2.9
Sodium, dissolved (mg/L as Na)	10	120	2.6	30	38	120	48	11	5.3	2.6
Sodium adsorption ratio	10	2.4	.2	.8	.7	2.4	1.3	.5	.3	.2
Percent sodium	10	44	12	22	10	44	28	19	13	12
Potassium, dissolved (mg/L as K)	10	13	5.2	7.9	2.4	13	9.3	7.1	6.2	5.2
Chloride, dissolved (mg/L as Cl)	10	5.6	1.0	3.3	1.5	5.6	4.4	3.3	2.0	1.0
Sulfate, dissolved (mg/L as SO_4)	10	500	6.0	140	160	500	220	54	28	6.0
Fluoride, dissolved (mg/L as F)	10	.3	.0	.1	.1	.3	.2	.1	.1	.0

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
	Station 06340528, West Branch Antelope Creek watershed, Continued									
Silica, dissolved (mg/L as SiO_2)	10	11	3.3	8.0	2.7	11	11	7.8	5.6	3.3
Arsenic, dissolved (µg/L as As)	1	1	1	--	--	--	--	--	--	--
Barium, dissolved (µg/L as Ba)	1	100	100	--	--	--	--	--	--	--
Beryllium, dissolved (µg/L as Be)	1	10	10	--	--	--	--	--	--	--
Boron, dissolved (µg/L as B)	10	190	10	80	60	190	130	60	40	10
Cadmium, dissolved (µg/L as Cd)	1	1	1	--	--	--	--	--	--	--
Chromium, dissolved (µg/L as Cr)	1	10	10	--	--	--	--	--	--	--
Cobalt, dissolved (µg/L as Co)	1	0	0	--	--	--	--	--	--	--
Copper, dissolved (µg/L as Cu)	1	3	3	--	--	--	--	--	--	--
Iron, dissolved (µg/L as Fe)	10	380	20	160	130	380	290	110	60	20
Lead, dissolved (µg/L as Pb)	1	3	3	--	--	--	--	--	--	--
Manganese, dissolved (µg/L as Mn)	10	120	20	49	27	120	50	45	36	20

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
	Station 06340528, West Branch Antelope Creek watershed, Continued									
Molybdenum, dissolved (µg/L as Mo)	10	10	1	6	5	10	10	6	1	1
Nickel, dissolved (µg/L as Ni)	1	2	2	--	--	--	--	--	--	--
Strontium, dissolved (µg/L as Sr)	10	1,200	40	310	350	1,200	420	180	68	37
Vanadium, dissolved (µg/L as V)	1	.4	.4	--	--	--	--	--	--	--
Zinc, dissolved (µg/L as Zn)	1	0	0	--	--	--	--	--	--	--
Aluminum, dissolved (µg/L as Al)	3	20	0	--	--	--	--	--	--	--
Lithium, dissolved (µg/L as Li)	3	30	4	--	--	--	--	--	--	--
Selenium, dissolved (µg/L as Se)	1	0	0	--	--	--	--	--	--	--
Dissolved solids, residue at 180°C (mg/L)	1	626	626	--	--	--	--	--	--	--
Dissolved solids, sum of constituents (mg/L)	10	981	48	301	297	981	462	151	103	48
Dissolved solids (tons per day)	7	8.10	.03	2.82	2.88	8.14	4.78	2.65	.24	.03
Dissolved solids (tons per acre-foot)	10	1.33	.07	.42	.40	1.33	.64	.20	.14	.07

Summary of water-quality data for the Hay Creek and West Branch Antelope Creek watersheds--Continued

Water-quality property or constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Number of samples	Maximum	Minimum	Mean	Standard deviation	95	75	50	25	5
	Station 06340528, West Branch Antelope Creek watershed, Continued									
Nitrogen, ammonia, dissolved (mg/L as NH_4)	1	0.01	0.01	--	--	--	--	--	--	--
Mercury, dissolved (µg/L as Hg)	1	.0	.0	--	--	--	--	--	--	--
Alkalinity, laboratory (mg/L as $CaCO_3$)	10	260	26	94	70	260	120	66	42	26
Noncarbonate hardness (mg/L as $CaCO_3$)	10	270	1	78	93	270	130	28	18	1
Potassium 40, dissolved (pCi/L as K^{40})	1	8.2	8.2	--	--	--	--	--	--	--