EVALUATION OF A WATERSHED MODEL TO SIMULATE SEDIMENT TRANSPORT IN A SMALL AGRICULTURAL WATERSHED IN INDIANA

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CONVERSION FACTORS AND ABBREVIATIONS

Inch-pound units in this report may be converted to metric (International System) units by using the following conversion factors:

Multiply inch-pound unit	By	To obtain metric units
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
inch per hour (in/hr)	25.4	millimeter per hour
mile (mi)	1.609	kilometer
pound per square foot (lb/ft^2)	4.882	kilogram per square meter
square mile (mi^2)	259.0	hectare
ton	0.9072	tonne
ton per acre (ton/acre)	2.242	tonne per hectares
ton per day (ton/d)	0.9072	tonne per day

Langleys per day may be converted to metric units of watts per square centimeter if multiplied by 1,005,000.

Degree Fahrenheit (°F) may be converted to degree Celsius (°C) by using the following equation:

$$°C = 5/9 (°F - 32).$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

The streamflow and sediment components of the watershed model, Hydrological Simulation Program-Fortran, were evaluated by calibration, verification, and sensitivity analysis using 2 years and 9 months of data collected from the 2.7 square-mile Hooker Creek watershed. The results of modeling are presented by a quantitative comparison of measured to simulated data, a qualitative discussion of model performance, and a quantitative description of model error.

The model incorporates precipitation, streamflow, and sediment-concentration data, collected at 5-minute intervals, and climatic data collected daily. Sixteen storms that produced more than 0.7 inch of rainfall each were used for calibration and verification of the model. Calibration extended from October 1981 through December 1982 and included 10 storms. Verification extended from February 1983 through June 1983 and included six storms.

Hydrographs of simulated sediment concentration generally have smaller peaks and longer recessions than do the hydrographs of measured data. The mean simulated peak for sediment concentration is 34 percent of the mean measured peak. Sediment discharged into long channel sections is assumed in the model to mix immediately and completely with water in the section. The assumption results in attenuation of the simulated peaks and prolonging of the simulated recessions. Addition of channel sections to increase the validity of the assumption decreased the accuracy of the simulated streamflow.

Because the model predictions of surface runoff during low-intensity rainfall for the calibration and verification periods were overly large compared to measured values, predicted sediment concentration and discharge also were overly large. Mean simulated sediment concentration and sediment discharge are 42 and 45 percent greater than the measured means of the low-intensity storms. Rainfalls of about 0.25 inch per hour are mostly absorbed by the soil, but varying model parameters during calibration could not decrease the predicted volume of surface runoff from the low-intensity storms without increasing the errors during other periods.

The mean absolute difference between measured and simulated sediment concentrations during storms used for calibration was 1,190 milligrams per liter, which is 45 percent less than the mean for the measured concentrations. The error analysis of the calibration data indicates that:

1. The largest errors, as a percentage of the measured characteristics, are associated with simulated maximum streamflows and average sediment discharges. The root-mean-square errors were 93 and 102 percent of the measured characteristics for streamflow and sediment discharge, respectively;

2. percentage error was not related to the size of the storm; and

3. the effect of inaccurate rainfall records, low-intensity rainfall, spring flushout, and frozen ground caused errors in simulating sediment transport throughout the year.

Most of the storms used to verify the model occurred during the spring and were small and of low intensity. Two characteristics of the simulated hydrographs that were apparent during calibration also were evident during verification: (1) Simulated streamflow increases sooner than measured flow; and (2) the simulated concentrations generally are higher than the measured concentrations during the low-intensity storms during spring. The model simulates an overly large percentage of surface runoff and an overly large sediment discharge during those storms. Mean simulated sediment concentration for low-intensity storms used in model verification is 42 percent greater than the mean measured concentration. The mean simulated sediment concentration for the calibration storm on April 17, 1982, is 43 percent greater than the measured concentration, possibly indicating that the accuracy of the model was similar during its calibration and verification.

INTRODUCTION

From 1980 to 1984, hydrologic data were collected by the U.S. Geological Survey from 20 small mined and unmined watersheds in the surface-mining areas of the eastern United States. During the first phase of the project, the data were used to describe the hydrology of the watersheds. During the second phase, the data were used to test two watershed models for their ability to simulate streamflow; the testing was limited to model calibration. During the third phase, the data were to be used to verify the calibrated models. The Geological Survey's coal-hydrology program ended before either model was tested for its ability to simulate sediment transport. However, simulations were made to test the ability of one of the models to simulate the detachment of sediment by rainfall, scour by surface runoff, and transport and deposition of sediment in a small watershed.

Purpose and Scope

The purpose of this report is to evaluate the sediment and streamflow components of the watershed model, Hydrological Simulation Program—Fortran (HSPF) when applied to a 2.7 mi^2 (square mile) agricultural watershed. The evaluation uses results from model calibration, sensitivity analysis, and verification, and includes a discussion of the ability of the model to simulate sediment transport. Results of model simulations include:

1. Graphs of measured and simulated streamflow, sediment concentration, and sediment discharge;

2. tables of measured and simulated streamflow, sediment concentration, and discharge;

3. error analysis of the simulated streamflow, sediment concentration, and discharge;

4. a table of model parameters after calibration; and

5. a table showing the sensitivity of selected model parameters.

Release of version 7.0 of HSPF was evaluated, and the evaluation was done from August 1985 to October 1985.

Watershed

Hooker Creek is a gently rolling watershed composed of glacial drift overlain by about 5 ft (feet) of loess. The loess is the parent material for the silt-loam soils that cover the entire 2.7-mi^2 watershed. Generally, the first 1 ft of the soil is the A horizon, and the next 4 ft is the B horizon. Within the B horizon, about 2.5 ft down from land surface, is a 1-ft fragipan. The A and B horizons are comprised of about 25 percent clay, 65 percent silt, and 10 percent sand.

About 95 percent of the watershed is used for farming, and the remaining 5 percent of the land, mostly near the main channel, is forested. Corn and beans are the primary crops, which usually are grown using conventional tillage practices. Tillage and planting are done in April and May, harvesting is done from September through November, and some fields are plowed following the harvest. More than one-half of the steeper slopes next to the primary streams are covered with forests and shrubs. Flood-plain areas are covered with trees or other plant species. Housing is single dwelling, but just outside the eastern boundary of the watershed is the small town of Lewis. Except for the State highways, roads have a gravel surface. These features are shown in figure 1.

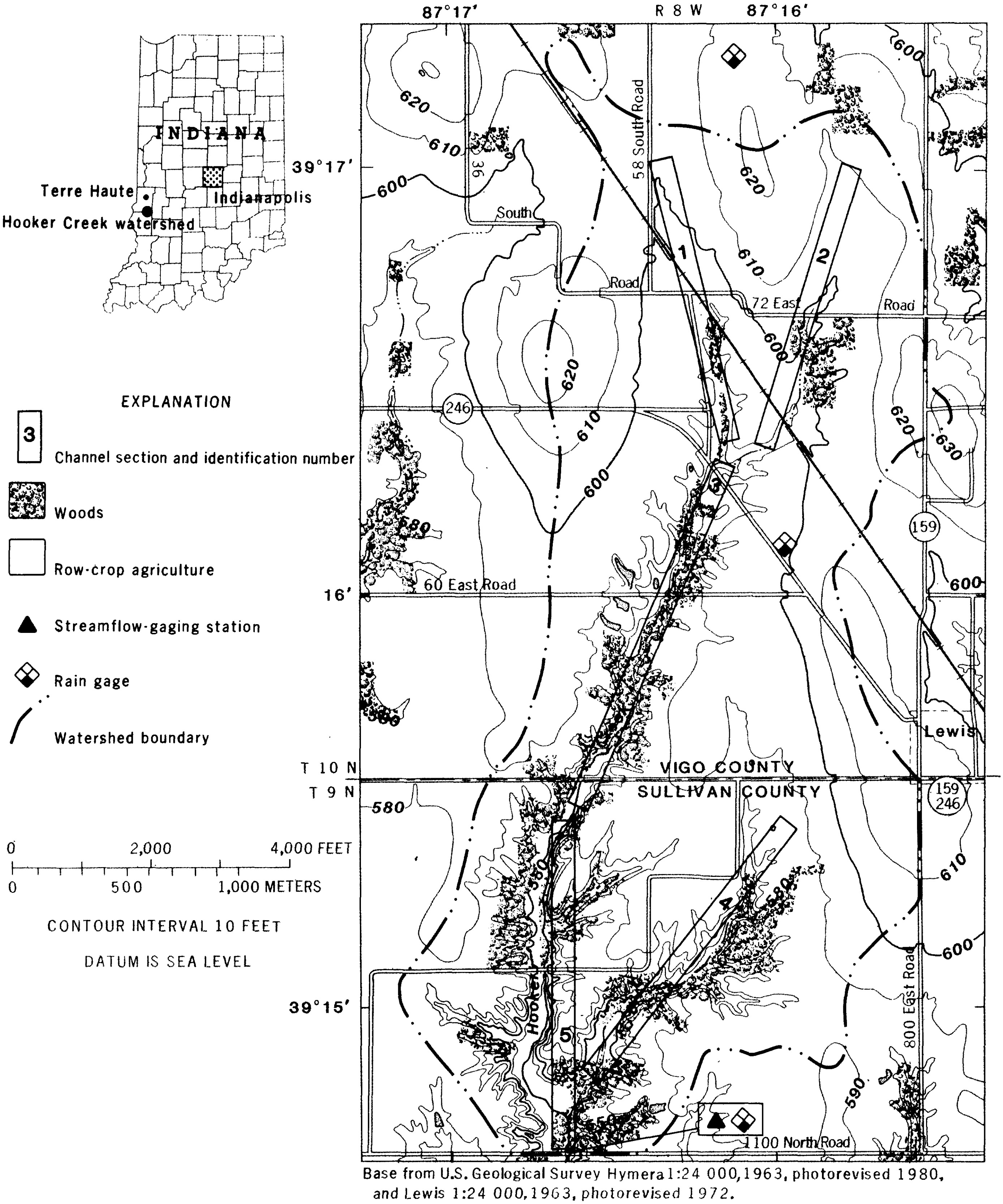

Figure 1.-- Location, topography, and data-collection sites, Hooker Creek watershed.

Data Base

The time-series data collected in and near the Hooker Creek watershed and used as input and calibration data are listed in table 1. As the footnotes of the table indicate, data for model analysis were collected from two sites: at the watershed outlet, and at a climate station 12 miles east of the watershed. The location of the data-collection site for rainfall, streamflow, and sediment concentration is shown in figure 1.

Table 1.--Description of data collected for model evaluation

[ft^3/s; cubic feet per second; in., inches; mg/L, milligrams per liter; ly/d, langleys per day; °F, degrees Fahrenheit]

Station number	Type of data	Period of record	Time interval of data	Range of data
03342110[1]	Streamflow	10/80-6/83	5 minutes	0-683 ft^3/s
391438087164000[1]	Precipitation	10/80-6/83	5 minutes	0-4.78 in. per storm
03342110[1]	Sediment concentration	10/80-6/83	As often as 5 minutes	0-12,000 mg/L
391253087021201[2]	Solar radiation	10/80-6/83	Daily	9-685 ly/d
391253087021201[2]	Air temperature	10/80-6/83	Daily	-22.9 to 93.2 °F

[1]Station located at bottom of figure 1.
[2]Data collected from a climate station 12 miles east of the watershed.

Although three rain gages were at the Hooker Creek watershed, the only data used in the model evaluation are from the southern gage (bottom of fig. 1). The record for the northern gage was not sufficiently complete for the evaluation. No data were available during the 2¼-year calibration, and 2 months of data were not available during the middle of the 6-month verification period. Also, final processing of data from the northern gage was not done because of difficulties in new processing programs required for the new type of rain gage at the site. The rain gage at the center of the watershed was not used on the basis of results from a previous model study at Hooker Creek (Lumb, A. M., and others, U.S. Geological Survey, written commun., 1985). Simulations of improved accuracy were possible during the previous study only by using data from the southern rain gage as opposed to using data from the southern and center rain gages together; therefore, the southern gage was used in this study. However, records from the central rain gage were used to replace missing records from the southern gage.

The streamflow record for Hooker Creek near Lewis, Indiana, was rated "good" during station analysis for the entire period of record. However, the record is least accurate for low flows because of the variation in elevation of the streambed, which affects the stage/discharge relation. The formation of ice in the channel also affected the stage/discharge relation during January 1981 and 1982. Instantaneous discharges at 5-minute intervals were deleted from the record if the effect from ice was severe. Otherwise, the streamflow record was adjusted for the effect of ice. The streamflow record was not affected by ice during the winter of the verification period. The largest measured streamflow was 528 ft^3/s (cubic feet per second), but the stage/discharge rating curve was extended to 683 ft^3/s (table 1) for one unmeasured storm that occurred on September 1, 1982. The extension was made by following the same trend as that of past rating curves.

Data describing the watershed characteristics were obtained from several sources. The physical dimensions, slopes, and orientation of the watershed were obtained from the Lewis and Hymera topographic maps of the U.S. Geological Survey. The values for parameters that affect the discharge of water and sediment were those either used by other modelers, obtained from published sources, or estimated by calibration. Observations made in the watershed during several trips to the data-collection sites also were used to determine the most accurate estimates for some of the parameters.

Rainfall patterns are related to the type of storm. Frontal storms are common during late winter and early spring and are characterized by rainfalls of low, steady intensity and long duration. Typically, during the summer, convective thunderstorms produce short-duration rainfall of large intensity near the beginning of the storm. Rainfall patterns for other parts of the year either are similar to or are mixtures of the two patterns described.

Solar-radiation and air-temperature data were collected from a climate station 12 mi (miles) east of the watershed. These data were used as input in the model, Precipitation-runoff modeling system (PRMS) (Leavesley and others, 1983), to calculate potential evapotranspiration for input to HSPF. Climatic parameters in PRMS were adjusted so that the output from PRMS for potential evapotranspiration is similar to the lake-evaporation estimate determined by the National Weather Service (NWS) (Farnsworth and others, 1982). The long-term average evaporative potential estimated by the NWS is about 35 in.; evaporative potential; PRMS calculated 35.7 in. for 1981 and 34.4 in. for 1982.

Data from 10 storms were used for calibration, and data from six storms were used for verification (table 2). The 16 storms were chosen because the streamflow and precipitation records were continuous during the storms, and usually about 10 sediment-concentration samples per storm were available to construct a concentration hydrograph.

Table 2.--Size and peak flow of calibration and verification storms

[in., inches; ft^3/s, cubic feet per second]

Calibration storms				Verification storms			
Date	Volume of rain (in.)	Volume of runoff (in.)	Peak flow (ft^3/s)	Date	Volume of rain (in.)	Volume of runoff (in.)	Peak flow (ft^3/s)
5/18/81	1.18	0.69	258	2/1-2/83	2.90	0.94	126
3/16/82	.69	.72	278	3/20-21/83	.91	.66	122
3/18-19/82	1.25	.95	165	4/1-2/83	.95	.67	122
4/16-17/82	1.20	.39	102	4/13-14/83	2.38	1.36	221
5/29/82	2.08	1.35	496	4/30/83	1.77	.30	229
6/7/82	.57	.21	109	5/1/83	1.65	.72	193
7/8/82	2.80	1.36	579				
7/10/82	.95	.15	51				
9/1/82	4.78	2.09	683				
12/24/82	1.23	.94	246				

In the following unnumbered table, rainfall, in inches, is compared for Hooker Creek with that for a long-term gage (Terre Haute), and with that for rain gages in other watersheds within a 10-mi radius of Hooker Creek. The purpose of the comparison is to demonstrate that rainfall data for the watershed are similar to nearby rainfall data and to a long-term average rainfall. The Hooker Creek rainfall listed in the table is for the rain gage used in the simulations, U.S. Geological Survey station number 391438087164000. This gage also is referred to as the southern gage in the text and is located at the bottom of figure 1. The Terre Haute rain gage is about 15 mi northwest of Hooker Creek. The other gages are to the north, east, and south of Hooker Creek.

Station name	Station owner	Station number	Precipitation during period 1981	1982	30-year average
Terre Haute	NOAA[2]	8723	48.79	47.08	38.41[2]
Hooker Creek	USGS[3]	391438087164000	37.94	46.57	---[1]
Big Slough Creek	USGS	392233087135000	40.36	42.38	---
Pond Creek	USGS	391335087031800	39.12	49.16	---
Sulfur Creek	USGS	390955087171800	31.39	42.16	---

[1]Data not available.
[2]National Oceanic and Atmospheric Administration.
[3]U.S. Geological Survey.

The rain gages closest to the study area indicate that Hooker Creek watershed had typical rainfall. The 1981 rainfall at most gages is near normal, but the 1982 rainfall is greater than normal because of rainfall from a few large summer storms. Rainfall at the Terre Haute and Sulfur Creek rain gages in 1981 are the only atypical volumes for the general area during the 2 years. The range in precipitation among the rain gages for 1981 is about 17.5 in. and indicates the potential for local variability in rainfall because of intense, local, summer thunderstorms.

MODEL DESCRIPTION

The choice of a watershed model was based on the author's previous work with HSPF (Johanson and others, 1981) and PRMS (Leavesley and others, 1983). In a previous study (Lumb, A. M., and others, U.S. Geological Survey, written commun., 1988), HSPF was more accurate in simulating streamflow than was PRMS for Hooker Creek. Because accurate simulation of streamflow is prerequisite to an accurate simulation of sediment transport, the HSPF model was used in this study. In addition, HSPF can simulate the deposition and resuspension of sand, silt, and clay within a channel, whereas PRMS could not.

In this section, the HSPF model is described briefly and in general terms. HSPF will be described in terms of its classification and structure; then the design chosen and the components used to simulate the watershed processes are described.

HSPF can be classified as a deterministic, continuous-simulation, distributed-parameter model. The model is deterministic because it simulates the important hydrologic processes (precipitation, surface runoff, infiltration, evapotranspiration, and others) without any stochastic components. The processes are simulated continuously through storm and nonstorm periods. HSPF is a distributed-parameter model because elements are used that are assumed to be uniform internally. Two types of elements used are the pervious land segment and the channel section. In the pervious land segment, surface and subsurface processes, such as surface runoff and infiltration, are simulated. Within the channel section, processes, such as flow routing and interchange of sediments with the streambed, are simulated.

The structure of the model enables the continuous simulation of a comprehensive variety of hydrologic and water-quality processes. The modular structure enables the user to activate as few or as many of the model components as needed. Output from one component is capable of being input to one or more of several other components. The model can predict changes over time for most variables at any point in the system as well. This flexibility of the model structure facilitates the development of the conceptual model of the watershed system.

The design of the conceptual model for Hooker Creek consists of one pervious land segment and five channel sections(fig. 1). This design resulted in the most accurate simulation of measured flow and incorporated the smallest number of pervious land segments and reaches (Lumb, A. M., and others, U.S. Geological Survey, written commun., 1988). Within the pervious land segment, several hydrologic and sediment-related processes are simulated. At the land surface, the instantaneous rainfall at 5-minute intervals is divided into surface and subsurface storages. Infiltration, evapotranspiration, surface runoff, interflow, and ground-water flow rates are calculated from the storages. Total streamflow is the sum of surface runoff, interflow, and ground-water flow. Erosion of sediment from the pervious land segment begins by rainfall detachment and by scour from surface runoff. The sediment detached by rainfall either washes off, reattaches to the soil matrix, or is kept in storage as detached sediment. Method 1, described in the HSPF user's manual (Johanson and others, 1981, p. 180-181), was used to simulate the washoff and scour of sediment. The reader is referred to the manual for an explanation of the equations used in Method 1 and of other equations used in HSPF. Water and sediment are discharged uniformly into each channel section. The water flows through the section according to the continuity equation and a rating table that relates streamflow to the volume of water in the section.

The sediment in the channel sections is assumed to be uniformly dispersed and to be moving at the same velocity as that of the water. Sand, silt, and clay can be deposited on or removed from the channel bed. A power equation calculates the capacity for sand to be transported down the section. The sand that cannot be transported is deposited. The deposition and scour of silt and clay are calculated by equations that require values for particle density, fall velocity, and shear stress to begin scour and deposition. Other options for more comprehensive sediment transport in the sections are available in the model, but were not used in this study.

EVALUATION OF MODEL

Calibration

The calibration will be discussed in terms of the ability of the simulations to approximate the measured values. The data to calibrate the model are listed in table 3 and are shown in figure 2. The daily sediment concentration and discharge listed in table 3 are calculated by using the sediment concentration and discharge hydrographs for the duration of the storm (fig. 2) and by estimating parts of the hydrographs not defined by the storm data. These undefined parts correspond to small values of each parameter and to a small percentage of the daily sediment concentrations and discharges.

Calibration of a sediment model requires accurate recording of precipitation, simulation of streamflow, and simulation of sedimentation processes. Therefore, part of the discussion of calibration concerns the adequacy of the precipitation record and the ability of the model to simulate flow. First, examples of how the precipitation record adversely affects model output are discussed. Second, examples of how limitations in model design and components affect the simulation of streamflow are described. Finally, the ability of the model to simulate the basic sedimentation processes is discussed.

Table 3.--Measured values of streamflow, sediment concentration, and sediment discharge for the duration of the storm and for the day, and values predicted during model calibration

[ft^3/s, cubic feet per second; mg/L, milligrams per liter; ton/d, tons per day; M, measured; S, simulated]

Date of storm	Type of data	Mean streamflow		Mean sediment concentration		Mean sediment discharge		Maximum streamflow (ft^3/s)	Maximum sediment concentration (mg/L)	Maximum sediment discharge (ton/d)
		Storm (ft^3/s)	Day (ft^3/s)	Storm (mg/L)	Day (mg/L)	Storm (ton/d)	Day (ton/d)			
5/18/81	M	185	50	2,330	900	1,170	236	258	3,910	2,270
	S	166	48	2,210	981	1,030	256	222	2,340	1,410
3/16/82	M	139	52	4,230	1,440	2,100	675	278	12,000	6,630
	S	113	39	2,160	775	746	236	218	2,640	1,550
3/19/82	M	62	82	1,560	1,120	400	267	165	4,280	1,750
	S	44	58	1,460	1,100	268	188	125	2,110	698
4/17/82	M	58	7	1,260	363	81	53	102	2,080	539
	S	74	8	1,800	548	174	96	116	2,070	647
5/29/82	M	a	98	3,720	b	1,620	b	240	6,270	3,380
	S	144	114	2,000	1,530	775	825	155	2,350	1,400
6/7/82	M	a	15	4,880	847	983	142	110	11,800	2,410
	S	2	1	174	51	1	.2	2.3	883	4
7/8/82	M	295	99	3,190	1,080	3,080	1,050	579	11,600	11,100
	S	372	123	3,400	1,640	3,570	1,170	679	3,720	6,800
7/10/82	M	38	11	2,940	630	332	55	51	8,630	1,090
	S	89	23	2,050	763	494	115	112	2,210	658
9/1/82	M	248	152	1,640	995	1,310	860	683	9,680	11,800
	S	459	279	2,790	1,750	4,490	2,730	1,440	4,070	15,800
12/24/82	M	104	68	1,230	761	473	277	246	3,540	1,940
	S	88	55	1,710	1,120	477	231	210	2,360	1,310

[a]Program which calculated this number caused an error condition; data not available.
[b]Data not available for the entire day.

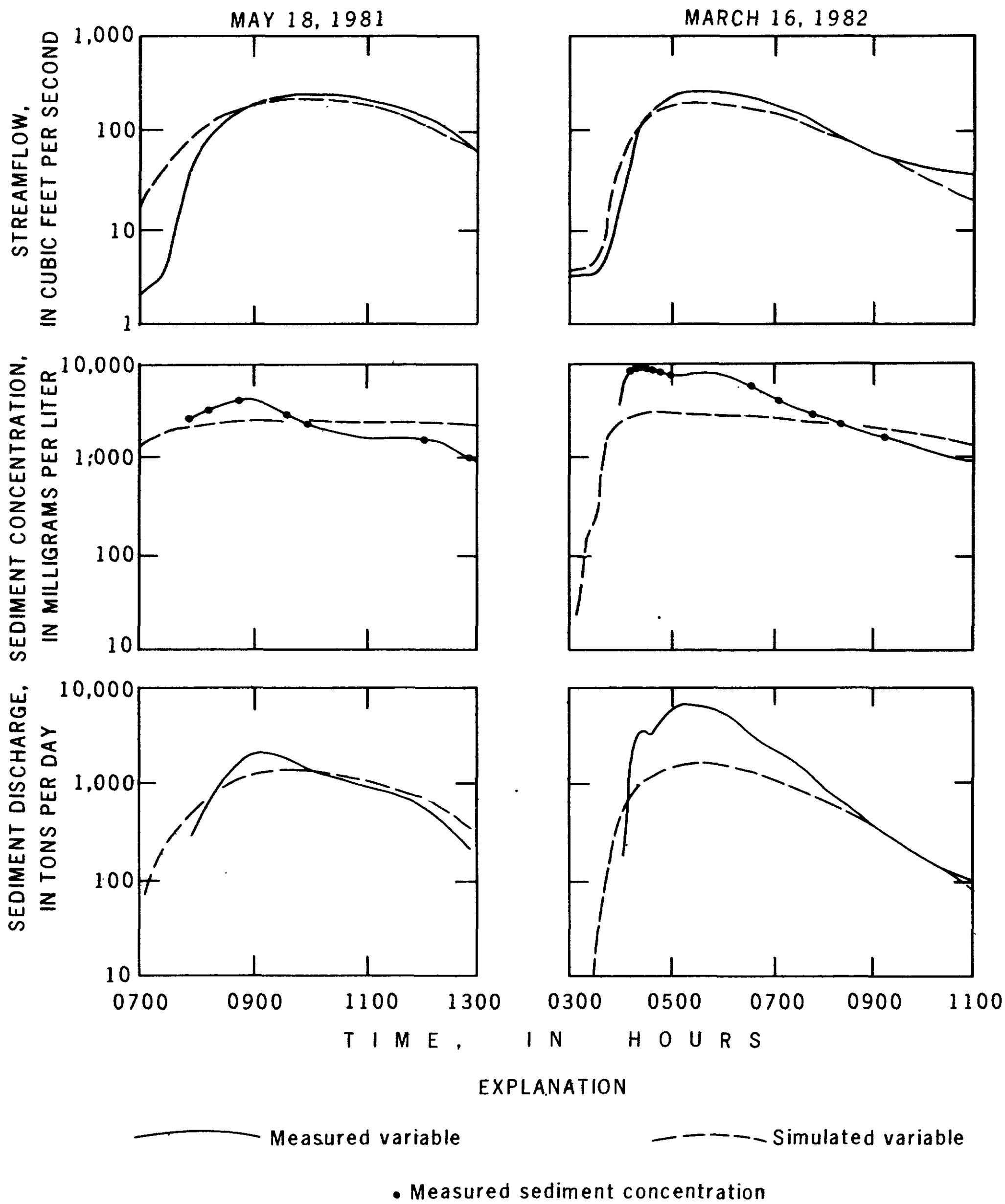

Figure 2.-- Measured values of streamflow, sediment concentration, and sediment discharge and values predicted during model calibration.

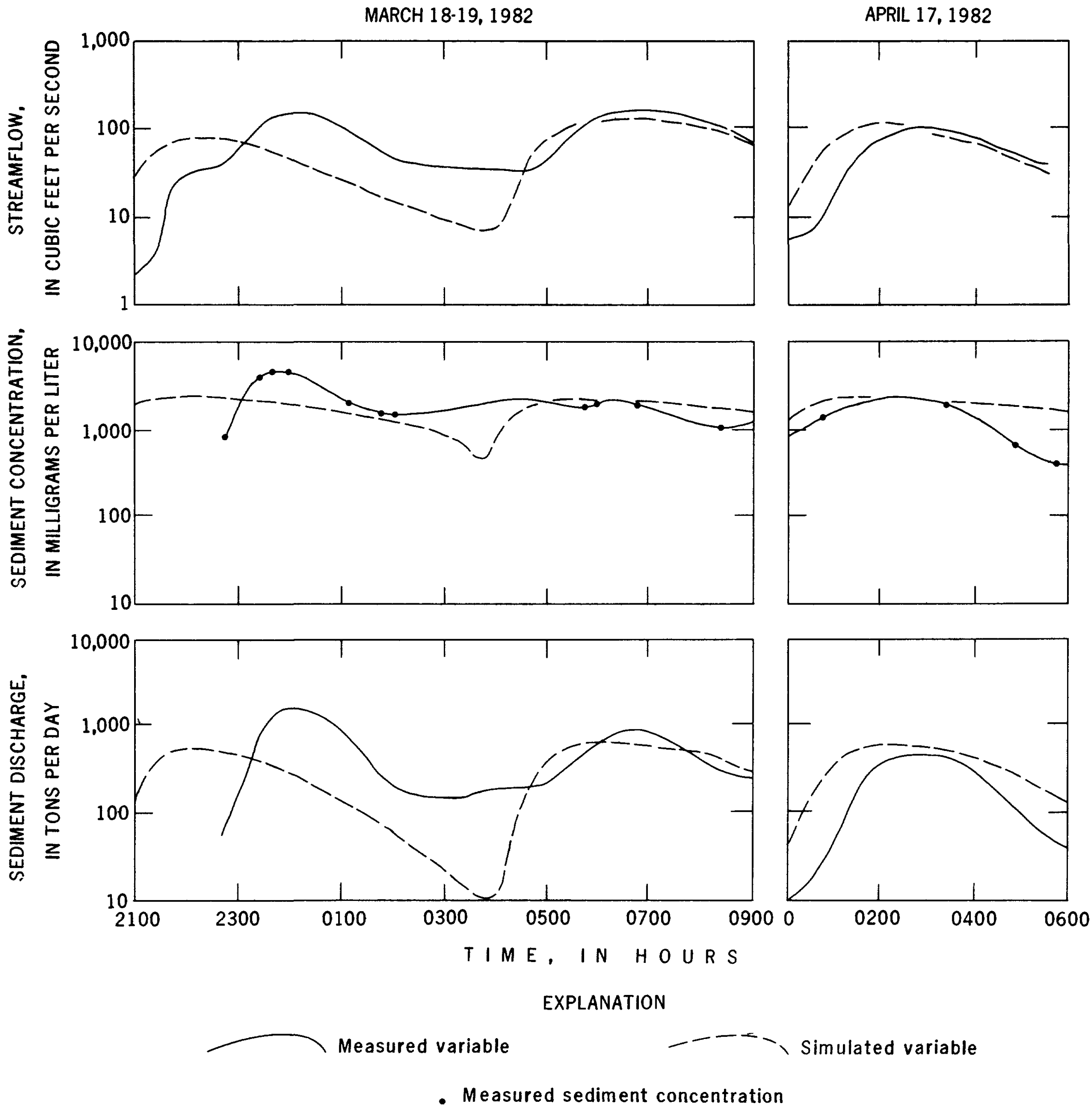

Figure 2.-- continued

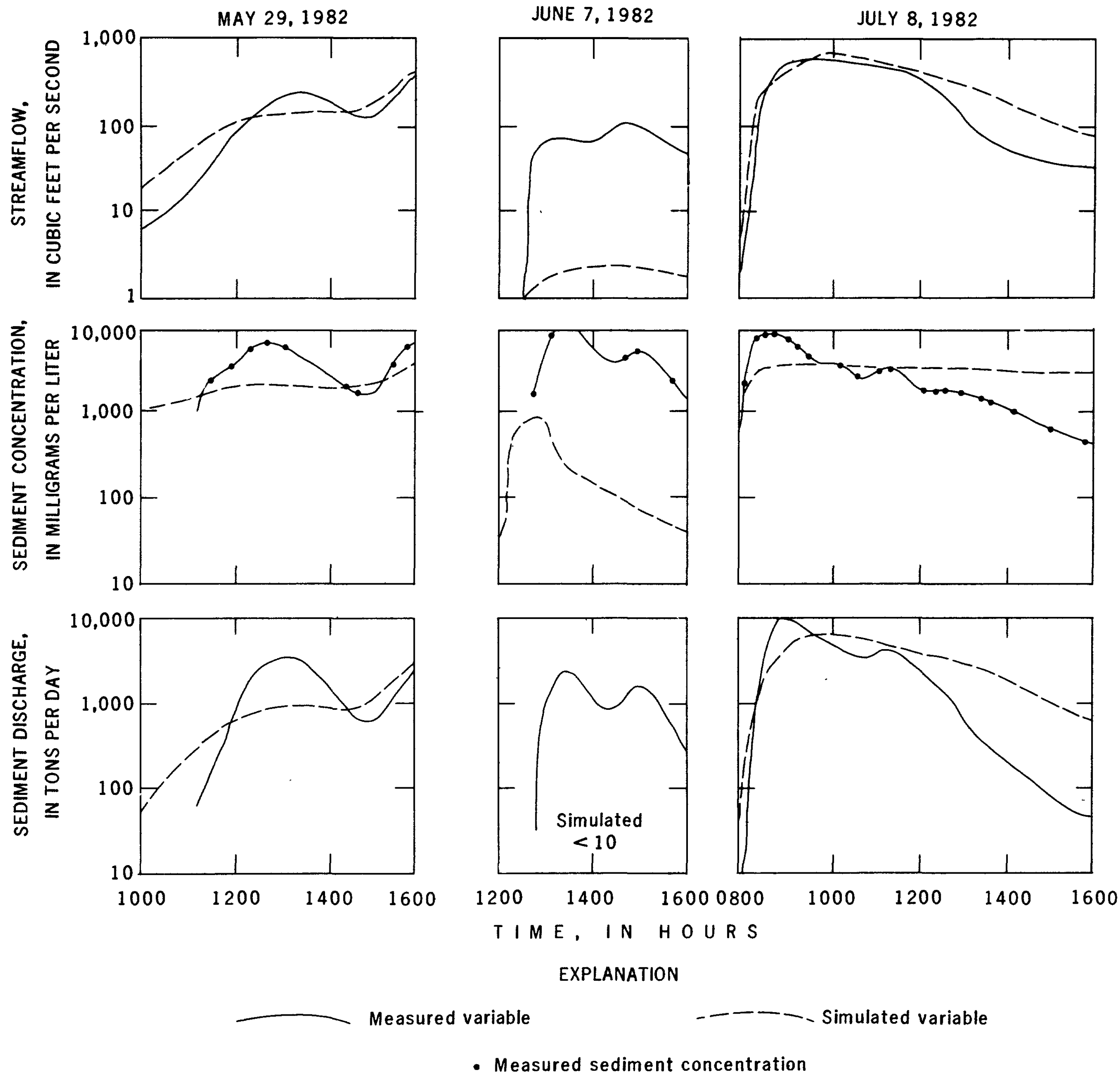

Figure 2.-- continued

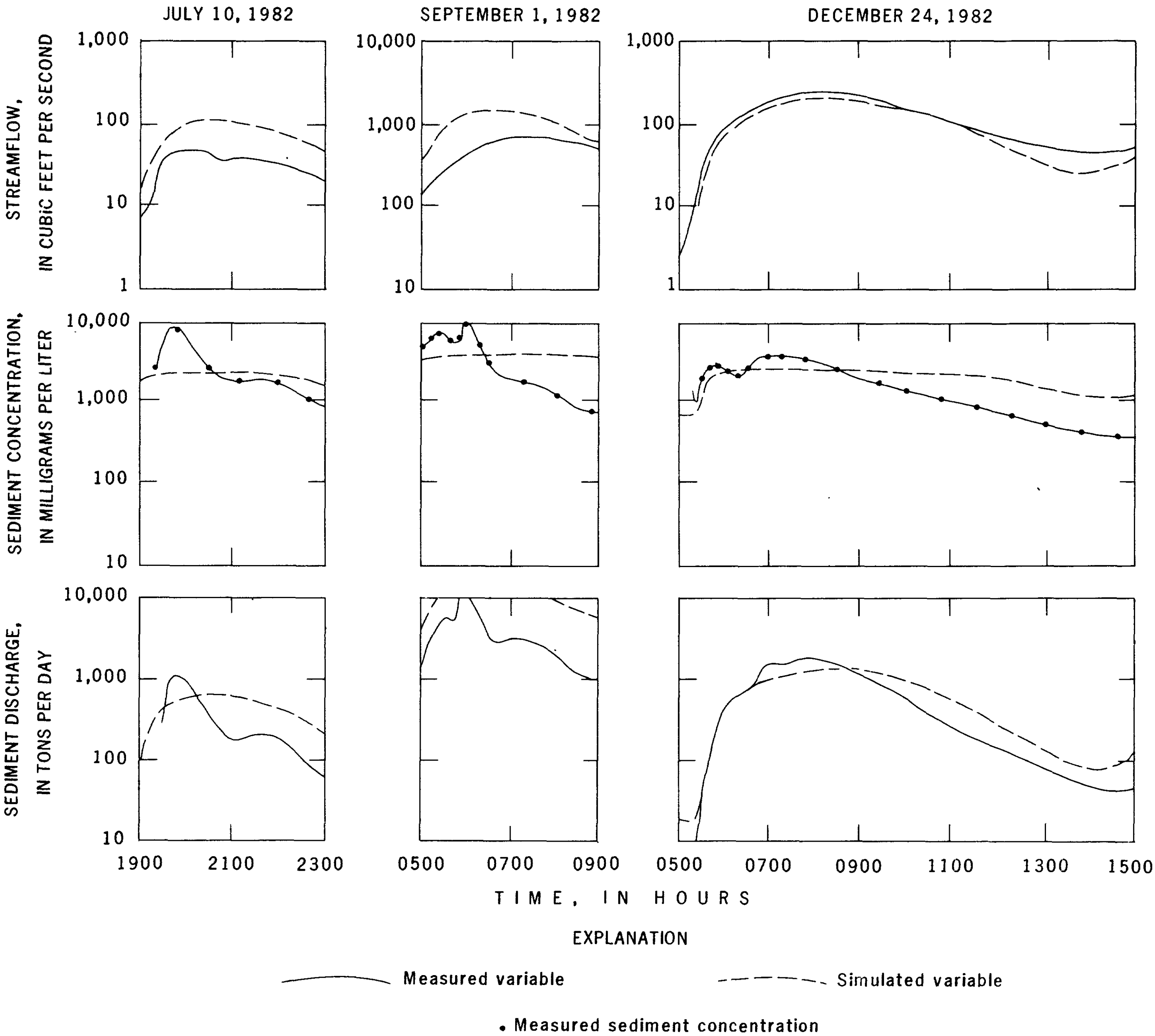

Figure 2.-- continued

Effects of Accuracy of Precipitation Records on Simulation

Hydrographs for simulated streamflow and sediment characteristics often are in error because the quantity of recorded precipitation does not accurately represent the precipitation for the entire watershed. Measured streamflow in the hydrograph for June 7, 1982 (fig. 2), is large compared to the volume of recorded precipitation. After a week of no rainfall, most rainfalls of about 0.5 in. do not produce a daily mean runoff of 15 ft^3/s (table 3). Apparently more rain fell than was recorded. About 0.9 in. of rain fell at the rain gage located in the center of the watershed. Because of the small quantity of recorded precipitation, all values for simulated parameters for June 7 are small. On July 10, 1982, the measured amount of precipitation apparently was overly large. The 1 in. of rainfall recorded on July 10 at the southern gage, which fell 2 days after a rainfall of 2.8 in., typically would cause more runoff than the measured rate of 11 ft^3/s. The northern rain gage (fig. 1) recorded only 0.29 in. of rainfall, which indicates that the 1 in. of rainfall measured at the southern gage, which represents the entire watershed, probably is too large. Precipitation record was missing for July 10, 1982, at the rain gage in the center of the watershed.

Some hydrographs of simulated streamflow and sediment characteristics are in error because the areal distribution of precipitation is not always represented adequately by one rain gage. Two increases in streamflow were recorded during the first 4 hours of a storm on March 18-19, 1982 (fig. 2). The two increases indicate two periods of precipitation. However, all the precipitation was recorded during the early part of the storm. As a result, the simulated increase occurs early in the simulation period and is out of phase with the measured increase. The rain gage at the center of the watershed recorded about 0.2 in. of rainfall at about 2200 hours, which probably could have caused a second increase in streamflow.

As stated in the "Data Base" section, if rainfall records at other rain gages in the watershed had been complete, the additional data should have improved the simulation of rainfall for the entire watershed. However, the record from the southern gage represents the most accurate data for the entire simulation period.

Effects of Model Design and Components on Streamflow

An error in the time-distribution of streamflow causes an error in that of sediment data. The storms on March 18-19, 1982, and on April 17, 1982 (fig. 2), provide examples of a timing error. During these storms, the simulated streamflow increases sooner than the measured streamflow. The cause(s) for the early increase in the simulated streamflow is not certain. Shortening channel sections (and simultaneously changing the stage/discharge relation for those sections) did not delay the simulated increase but attenuated the peaks and prolonged the recessions. However, error in estimating the dimensions of the additional channel sections and in estimating the stage/discharge relations also may have caused the attenuated peaks. Whether additional channel sections would improve the timing of the increases is uncertain. Lengthening overland flow paths to delay the increase also attenuated the peaks and prolonged the recessions. Simulating an increased percentage of interflow and increasing surface storage had the same effect on the hydrographs as did lengthening flow paths.

Part of the reason for the early increase seems to be related to a need to simulate the tributary network. Tributaries increase the flow path by adding more channel length. Also, routing water into tributaries maintains the steepness of the peak in the streamflow hydrograph, whereas routing water across overland-flow paths to the main channel does not. The overall result of adding tributaries should be a delayed increase that has about the same steepness as before the tributaries were added. When tributaries to the main stream were added, the simulated increase was delayed somewhat. However, the simulated increase is still early as shown in several hydrographs of figure 2. Even if minor tributaries were added, the simulated increase probably would still be early. Another modeler (Lumb, A. M., U.S. Geological Survey, written commun., 1987) explained that increasing the storage capacity of the upper soil zone (UZSN in HSPF) may delay the simulated increase. However, the storage capacity was not changed during simulations used in this study.

An early increase is not as prominent for the storm of July 8, 1982. Rapid runoff from intense summer thunderstorms decreases the discrepancy between the time of increase for the hydrographs of measured and simulated streamflow.

Ability of Model to Simulate Sediment Transport

Parameters in the sediment component of HSPF were adjusted to correlate (1) estimates of gross erosion and sediment yield for individual years, and (2) measurements of sediment concentration and discharge during storms. Because calibration data were not available for estimating gross erosion, it was estimated by using the universal soil-loss equation (Wischmeier and Smith, 1978). A general analysis of gross erosion was done by dividing land use into two general categories: row-crop agriculture and forest. The long-term average of gross erosion was calculated to be about 8 (ton/acre)/yr (tons per acre per year). Because precipitation in 1981 was less than average and in 1982 was greater than average, the simulated gross erosion should be less than the calculated quantity of 8 (tons/acre)/yr for 1981 and more than 8 (tons/acre)/yr for 1982. Gross erosion is the soil that becomes detached from the soil matrix but does not necessarily leave the watershed. The quantities calculated, using the model, that correspond to gross erosion are DET (the quantity of sediment that is detached by rainfall) and SCRSD (the quantity of sediment that is scoured from the soil matrix by surface runoff). The sum of these two parameters should correspond to the value calculated by the universal soil-loss equation.

The net erosion, or sediment discharge, was estimated by a streamflow and sediment-discharge graph and by measurements of sediment concentration during storms. The graph was developed for Hooker Creek near Lewis, Indiana, and relates sediment discharge to the volume of runoff and to the rainfall intensity of the storm (Kilpatrick, F. A., and others, U.S. Geological Survey, written commun., 1988); this relation seems to be reasonably consistent. The yearly sediment discharge was calculated using the graph, and model parameters were adjusted until yearly simulated sediment discharge approximated the calculated value. This approach was used in the beginning of calibration to define roughly values of model parameters. Then, calibration data, which consisted of 5-minute streamflow and sediment-concentrations, were used to improve the accuracy of model-parameter values.

The calibration data of 5-minute sediment concentrations were derived by fitting a spline curve through values of sediment concentration measured during each storm. Each spline curve was reviewed and adjusted as necessary. The location on the curve of the measured sediment concentrations is shown in figure 2. Concentrations at 5-minute intervals were derived from the spline curves to facilitate comparison of measured and simulated data and to make statistical calculations of measured and simulated data using the available output-analysis program for HSPF, the ANNIE program (Lumb, A. M., and Kittle, J. L., U.S. Geological Survey, written commun., 1985). Although the measured curves are not actually measured at every point, the curves follow the probable trend of sediment concentration. Also, results from the statistical comparisons need to be used only as a general indication of simulation accuracy.

Initial calibration was based on two quantities calculated by HSPF that, when summed, correspond to sediment discharge: SCRSD and WSSD. WSSD is the quantity of sediment detached by rainfall that subsequently is washed off the watershed by overland flow. Parameters that affect these quantities were adjusted until the yearly simulated sediment discharges correlated to the calculated values as much as possible. Parameters affecting WSSD and SCRSD also were adjusted such that more sediment was lost by scour than by washoff. Generally, the erosion rate is greater for rill erosion than for sheet erosion (Meyer, L. D., Agricultural Research Service, oral commun., 1986).

An unexpected result from calibration is that simulated sediment discharge, when calibrated to yearly quantities derived from the graph (Kilpatrick, F. A., and others, U.S. Geological Survey, written commun., 1988), also simulated reasonable fits to sediment concentrations during individual storms. The shape of simulated hydrographs and the values of simulated mean concentration and mean discharge were not improved further by using the measured storm data in calibration. The graph of sediment discharge as a function of streamflow is a useful guide in calibration, because the storm data used for calibration are the same data used to construct the graph.

The simulated and calculated quantities for gross erosion and for sediment discharge are listed in table 4. The simulated gross erosion for 1981 is less than 8 (tons/acre)/yr, as it should be, but this rate may be smaller than would be expected. Precipitation for 1981 is only 2 in. less than the precipitation mean of 38.41 in., but the simulated gross erosion is about one-half the calculated gross-erosion mean. Sediment-related parameters possibly could be adjusted to increase the simulated gross erosion and, yet, not change substantially the reasonable quantity for simulated sediment discharge. However, to do the adjusting, the sediment parameters would have to be increased more than the values recommended from an earlier version of the model (Donigian and Davis, 1978, p. 66). Therefore, sediment parameters were not increased, and simulated gross erosion still was 4.2 tons/acre (table 4). Simulated gross erosion for 1982 is reasonable, although precipitation was 8 in. more than the mean for the year. However, the simulated sediment discharge for 1982 is 1 ton/acre (ton per acre) greater than the calculated quantity (table 4). The additional 1 ton/acre is almost exactly the quantity that sediment was overpredicted for a large storm on September 1, 1982. Sediment discharge from this storm greatly affected the yearly quantity of discharge. Reasons for the overprediction are discussed later in this section.

Table 4.--Simulated and calculated values for rates of gross erosion and sediment discharge

[<, less than; >, greater than]

Source of data	Gross erosion (tons per acre per year)		Sediment discharge (tons per acre per year)	
	1981	1982	1981	1982
Simulation	4.2	12	1.5	4.3
Calculation	<8	>8	1.7	3.3

Most simulated hydrographs of simulated sediment concentration shown in figure 2 have the same general shape when compared to the measured hydrographs--small peaks and high recessions. The simulated peak for mean sediment concentration is 34 percent of the mean measured peak. Adjustment of parameters that affect the availability of sediment do not improve the accuracy of the simulated hydrographs. An increased supply of sediment increased the peaks but not enough to equal measured peaks. At the same time, the simulated recessions were even higher than those in figure 2. Also, the mean sediment concentration and the total quantity of sediment discharged during the storms were overly large.

A reason that simulated sediment-concentration hydrographs have small peaks and high recessions may be related to the design of the channel system and by the assumption about how sediment mixes in the channels. Three channel sections are used to discretize the main channel. Use of only a few sections causes outflow to be too fast, and use of additional sections causes streamflow peaks to be too small and outflow to be too large. Although three sections are the best number to route streamflow, they apparently are too few to accurately simulate sediment transport down the channel. When sediment is transported off the land surface into a channel section, that sediment is assumed by the model to be distributed uniformly throughout the section. The distribution process seems to attenuate the peak and prolong the recession in the sediment-concentration hydrograph but not change the overall quantity of sediment discharged.

How the model simulates the addition of sediment from tributaries also affects the attenuation shown in the hydrographs of figure 2. About one-fourth of the watershed contributes sediment to a tributary near the outlet of the watershed (fig. 1). The sediment discharges almost directly to the outlet of the watershed. However, HSPF evenly distributes sediment from the tributary throughout the last channel section of the main stream, which essentially transfers sediment from the tributary to upstream in the main channel. Because discharge of the sediment is delayed by the transfer, the simulated peaks are attenuated and the recessions are prolonged. An increase in the number of channel sections would correct the problem just described but, as stated earlier in this section, also would increase error in the simulation of streamflow.

One exception to the pattern of the hydrographs of simulated sediment concentration is the hydrograph for April 17, 1982 (fig. 2). The measured and simulated peaks are almost equal, and the predicted overall sediment discharge is overly large. Mean simulated sediment concentration and sediment discharge are 42 and 45 percent greater than the measured means of the low-intensity storms. The reason for the exception may be that the model simulates an overly large percentage of surface runoff for the storm (about 80 percent surface runoff). On late April 16 and early April 17, rainfall was about 0.25 in/hr (inches per hour), most of which could have been absorbed by the soil. Example hydrographs of low-intensity storms are shown for April 1981 (fig. 2) when rainfall at Hooker Creek often was about 0.25 in/hr (Lumb, A. M., and others, U.S. Geological Survey, written commun., 1988). The simulated hydrographs show rapid rises and declines compared to the measured hydrographs, which show a large quantity of absorption and a large percentage of subsurface flow as reflected by their comparatively small peaks and mildly sloping recessions. If additional subsurface flow were simulated during the storm of April 17, 1982, then low surface runoff and little detachment of sediment would have been simulated. Low detachment would cause the simulated peak concentration to be smaller than the measured peak--a characteristic of simulated sediment-concentration hydrographs for large-intensity storms. A reduction in the percentage of surface runoff and an increase in the percentage of subsurface flow probably would not diminish the accuracy of the simulated streamflow hydrographs for low-intensity storms.

The hydrograph of simulated sediment concentration during the latter part of the storm on March 19, 1982 (fig. 2), also is caused by low-intensity rainfall. Again, the simulated peaks for concentration are similar to the measured ones. Adjusting parameters of the model to account for the increased absorption of low-intensity rainfalls could not be done for the same watershed and data used in model calibration during a previous study (Lumb, A. M., and others, U.S. Geological Survey, written commun., 1988).

Detached sediment can accumulate in and near channels during late fall and winter by wind deposition, freezing and thawing, and human activities that disturb the soil. Rainfall is limited during these seasons; therefore, the first major storm of the spring transports the accumulated sediment and the sediment normally detached by rainfall and scour. An example of the spring flushout is the storm of March 16, 1982 (fig. 2). The simulated streamflow is only slightly less than the measured streamflow, but the hydrographs for sediment concentration and discharge show that the simulated sediment discharge is well under the measured discharge. The large discrepancy between measured and simulated quantities for mean sediment concentration and mean sediment discharge for March 16 is listed in table 3. The discrepancy is not as great for storms later in the year when simulated streamflow is somewhat similar to measured streamflow.

The HSPF model can include sediment from other sources, such as wind deposition, but the option was not used in this study. Sensitivity analysis, which is described in the "Sensitivity Analysis" section, indicates that a greater or lesser supply of detached sediment in the uplands does not change the sediment yield. Possibly, additional sediment became available after the soil near the channels thawed and slumped into the channel. Then, the sediment does not need to be transported from the uplands but already is at the stream and can be transported from the watershed.

The effect of frozen soil on runoff is indicated by the streamflow and by sediment-concentration hydrographs for December 24, 1982 (fig. 2). After a period of freezing temperatures in December, the model generally underpredicted streamflow. Simulated streamflow is less than the measured, as on December 24, probably because surface runoff increased when the soil was frozen. Although simulated streamflow is less than measured, simulated sediment concentration is larger, again because of the effect of frozen soil. Frozen soil does not erode as easily as unfrozen soil. Soil was eroded by the model using the same potential for summer erosion, but potential for erosion actually decreases as the soil begins to freeze. Because the effects of frozen soil were not simulated, the storm on December 24 is the only one in which simulated streamflow was less than measured streamflow and sediment concentration was greater than the measured concentration.

Changes in erosion parameters over time and the effect of frozen soil on surface runoff can be simulated. Future calibration of the model could use the special-actions component to change the erosion parameters. However, an apparent problem developed in a previous study that used the snow component of the model to simulate freezing of the soil (Lumb, A. M., and others, U.S. Geological Survey, written commun., 1988). The simulation predicted that more than 7 in. of precipitation intercepted and subsequently evaporated yearly, compared to about 2.5 in. in simulations not using the snow component. The predicted extra 4.5 in. of interception loss resulted in a mass-balance error among precipitation input, the model outputs, and changes in storage. The reason for the mass-balance error is unknown.

The storm on September 1, 1982, produced the largest measured streamflow, and predicted streamflow and sediment parameters were overly large. Because the stage/discharge relation for Hooker Creek is not well defined at that flow (see the "Data Base" section), the quantity of measured streamflow is somewhat uncertain.

The quantity of sediment discharge is affected by sedimentation processes in the stream as well as on the watershed. Data for sediment parameters for the streambed were not available; therefore, values for the parameters were derived by simulating sedimentation processes in the stream according to some assumptions about the processes. Sediment eroded from the streambed was assumed to be small compared to the sediment derived from the land surface. The assumption was made because (1) the erodibility of streambed and of bank soil probably was about equal to that of soil in the watershed, and (2) the area of potential erosion for the stream is much smaller than that for the land surface. Another assumption is that erosion parameters would be adjusted so that more silt than clay would be eroded. The adjustments were made because the soil contains more silt than clay and because silt erodes more easily than clay. The values for the sedimentation parameters (TAUCS, TAUCD, and M), which produced the desired results, are listed in the "Supplemental Data" section, table 10. Simulated net erosion for silt and clay from the streambed during the 2-year calibration period was 248 tons and 210 tons, respectively. Typically, silt and clay were deposited by small storms and were eroded by moderate and large storms.

Sand transport also was simulated because data on particle-size distribution indicated that the percentage of sand in the total sediment load ranged from about 5 to 20 percent. Of the three equations available to simulate the transport of sand downstream, only the power equation was applicable for streamflow in Hooker Creek. However, for some unknown reason, all values chosen for the coefficient and exponent in the power equation would cause sand to be deposited. Also, the change in the quantity of sand that would be deposited because of changes in the parameters differed by only 5 to 10 tons after the $2\frac{1}{4}$-year calibration period.

The inability of the model to change the transport of sand was not because of a limited transport capacity. According to the transport equations, transport capacity for sand is limited only by the streamflow. Because of the lack of sensitivity in two parameters for transporting sand, their chosen values were simply 1.0 (see table 10 in "Supplemental Data" section)--that is, the coefficient and exponent in the power equation are 1.0. Sand in the streambed increased during the simulation by 190 tons.

The simulation errors are described in table 5. The following is an explanation about specific errors to which the numbers refer. Means and maximums of measured and simulated streamflow and sediment data were calculated for each storm. These averages and maximums of all the storms then were averaged. The simulated averages for all the storms are the ones analyzed for error. For example, the number 140 at the top of column 2 in table 5 is the mean of all the mean streamflows for the measured data. In column 4 on the same line, the number 53 means that the averages of simulated streamflow have a mean absolute error of 53 ft^3/s (cubic feet per second) when compared to the averages of the measured streamflows. The number 295 on the second line in column 2 is the average of all the maximum streamflows for the measured data.

Table 5.--Statistics from calibration on error in simulated streamflow, sediment concentration, and sediment discharge for the duration of the storms

[ft^3/s, cubic feet per second; mg/L, milligrams per liter. Numbers in parentheses are the error term divided by the value on the same line in column 2, then multiplied by 100]

Statistic	Mean for all storms, measured statistic	Mean for all storms, simulated statistic	Mean absolute error for the averages of the simulated statistic (percentage of measured)	Root mean square error for the averages of the simulated statistic (percentage of measured)	Standard error of estimate for the averages of the simulated statistic (percentage of measured)	Bias for the averages of the simulated statistic (percentage of measured)
Average streamflow (ft^3/s)	140	173	53 (38)	83 (59)	87 (62)	33 (24)
Maximum streamflow (ft^3/s)	295	391	138 (47)	274 (93)	294 (100)	95 (32)
Average sediment concentration (mg/L)	2,630	1,920	1,190 (45)	1,790 (68)	1,820 (69)	-709 (-27)
Maximum sediment concentration (mg/L)	7,380	2,490	4,890 (66)	6,040 (82)	3,950 (54)	-4,890 (-66)
Average sediment discharge (tons per day)	1,150	1,320	823 (72)	1,220 (106)	1,350 (117)	169 (15)
Maximum sediment discharge (tons per day)	4,300	3,130	2,010 (47)	2,690 (63)	2,690 (63)	-1,170 (-27)

Some observations and comparisons of the values in table 5 are discussed. The largest percentage errors listed in table 5 are those associated with simulated maximum streamflows and mean sediment discharges. The simulated mean sediment concentrations are smaller than the measured ones (table 5), mostly because of the small concentrations, when compared with the measured concentrations, for March 16 and June 7, 1982 (table 3). In general, the slightly large simulated average streamflow and the small simulated average sediment concentration caused simulated sediment discharge to be almost equal to the measured (table 5). However, the error in simulated streamflow may not cancel the error in simulated sediment concentration when predicting sediment discharge for other simulations.

Percent error did not increase with the size of the storm or with a specific time of the year. Errors, as a percentage of the measured mean, changed randomly with the size of the storm. The problems caused by inaccuracies in precipitation and streamflow records, low-intensity rainfall, spring flushout, and frozen ground resulted in errors in simulated sediment transport at times during the year.

Sensitivity Analysis

The sensitivity analysis was done to determine the sediment-related parameters that most affect sediment yield--that is, the model parameters that are most sensitive to variation. If the most sensitive parameters and the degree of accuracy of those parameters are known, the accuracy of the simulations can be assessed to some extent. Also, after sensitive parameters are determined, future model studies could improve the accuracy of the values selected for those parameters.

The parameters chosen for sensitivity analysis and the results of the analysis are listed in table 6. The parameters were chosen because a ±50 percent change in the parameters could cause substantial changes in SOSED, the sediment yield.

All but two of the parameters were sensitive. The two nonsensitive parameters, KRER and JRER, are the coefficient and exponent in the equation for rainfall detachment. Gross erosion always produces more sediment than a watershed can discharge by streamflow. However, for these parameters, the supply was so large that not even a change of -50 percent in the parameters changed SOSED.

The parameters that do change SOSED are the coefficients and exponents in the equation for washoff of detached sediment (KSER and JSER) and in the equation for scour of the soil matrix (KGER and JGER). Changes in the parameters that are exponents in the equations cause the largest differences in SOSED. Equal positive and negative changes in the coefficient for the washoff equation, KSER, cause an equal positive and negative difference in SOSED. However, the negative change in the coefficient for the scour equation, KGER, causes less difference in SOSED than does the positive change. Therefore, underestimating KGER may cause less error than overestimating KGER.

Table 6.--Sensitivity of sediment yield to each sediment-related model parameter

[(tons/acre)/yr, tons per acre per year]

Sediment-related parameter and its quantity[1]	Percentage change in the parameter	SOSED resulting from ±50 percentage change in the parameter [(tons/acre)/yr]	Percentage difference in SOSED from the 1982 calibration quantity of 4.31 (tons/acre)/yr
KRER	-50	4.31	0
(0.45)	+50	4.31	0
JRER	-50	4.31	0
(1.0)	+50	4.31	0
KSER	-50	3.57	-17
(0.06)	+50	5.05	17
JSER	-50	3.49	-19
(1.5)	+50	7.86	82
KGER	-50	2.99	-31
(0.15)	+50	7.13	65
JGER	-50	3.09	-28
(1.3)	+50	9.31	116

[1]KRER, the coefficient in the equation for detachment by rainfall;
JRER, the exponent in the equation for detachment by rainfall;
KSER, the coefficient in the equation for transport of detached sediment;
JSER, the exponent in the equation for transport of detached sediment;
KGER, the coefficient in the equation for scour by surface runoff;
JGER, the exponent in the equation for scour by surface runoff.

The parameters for the equation of scour, KGER and JGER, cause the greatest change in SOSED and are the most sensitive parameters. As mentioned in the first part of this section, the accuracy of the simulation is somewhat dependent on the accuracy of the most sensitive parameter. However, no guidelines were available for the choice of KGER and JGER. The only principle used to determine the value of the parameters was that they, and KSER and JSER, should produce a sediment yield that is similar to that calculated by the graph developed by F. A. Kilpatrick and others (U.S. Geological Survey, written commun., 1988). The parameters probably are not too erroneous. KGER possibly could be decreased and JGER increased, and SOSED still might be similar to its current quantities. If KGER and JGER are in error, then the relative quantities of sediment derived by scour and by washoff are in error. However, the combination of scour and washoff (sediment yield) seems to be reasonable for 1981 and 1982.

Verification

Calibration was used to adjust parameters of the model until the most accurate fit of the measured hydrographs and the smallest error in the simulated variables were obtained. Verification determines whether the calibrated model can simulate other storms with the same degree of accuracy as storms simulated during calibration. During verification, observations were made to determine if simulated streamflow and sediment hydrographs had the same characteristics as they did during calibration. Also, any new difficulties in correlating measured conditions when simulating the six verification storms were determined. The measured and simulated values from verification are listed in table 7.

Six storms, about 40 percent of the total number, were used for verification. However, the data-processing program called ANNIE (Lumb, A. M., and Kittle, J. L., U.S. Geological Survey, written commun., 1985), which produced the hydrographs and calculated the tabular data, did not output any information for the storm on February 1-2, 1983, and output only tabular data for the storm on May 1, 1983. Therefore, the results from simulating all six storms cannot be presented. The reason for the omissions by the program is unknown.

The storms are mostly the same type: low to moderate intensity and of long duration during the spring. Normally, the different types of storms would be divided equally among the calibration and verification data sets. However, the number of available storms for each type is too small to divide between the two data sets. Therefore, for this report, a variety of storm types were used for calibration and less were used for verification. A model needs to be calibrated adequately before it can be verified. The storms in 1983 provided at least a limited test of the model's ability to duplicate its accuracy for 1981 and 1982 storms.

Two characteristics of the simulated hydrographs that were apparent during calibration also are shown in figure 3: (1) simulated streamflow increases sooner than measured streamflow; and (2) the simulated concentrations generally are larger than the measured concentrations during the low-intensity storms of spring. The model apparently simulates an overly large percentage of surface runoff and an overly large amount of sediment erosion during those storms. Mean simulated sediment concentration for low-intensity storms used for model verification is 42 percent greater than the mean measured concentration. The mean simulated sediment concentration for the storm on April 17, 1982, used to calibrate the model, is 43 percent greater than the measured concentration, possibly indicating an accuracy during verification similar to that during calibration.

Table 7.--Measured values of streamflow, sediment concentration, and sediment discharge for the duration of the storm and for the day, and values predicted during model verification

[ft^3/s, cubic foot per second; mg/L, milligrams per liter; ton/d, tons per day; M, measured; S, simulated]

Date of storm	Type of data	Mean streamflow Storm (ft^3/s)	Mean streamflow Day (ft^3/s)	Mean sediment concentration Storm (mg/L)	Mean sediment concentration Day (mg/L)	Mean sediment discharge Storm (ton/d)	Mean sediment discharge Day (ton/d)	Maximum streamflow (ft^3/s)	Maximum sediment concentration (mg/L)	Maximum sediment discharge (ton/d)
3/20/83	M	78	38	868	424	215	108	123	2,060	619
	S	78	42	1,440	831	346	184	128	1,840	637
4/1-2/83[1]	M	38	24	571	550	86	50	122	2,170	714
	S	34	23	650	600	131	80	131	1,980	699
4/13-14/83[1]	M	128	50	1,330	440	530	150	221	2,380	1,360
	S	130	50	1,850	848	674	224	206	2,130	1,180
4/30/83	M	122	20	4,960	850	1,820	280	229	7,320	4,080
	S	250	51	3,060	901	2,060	409	300	3,150	2,530
5/1/83	M	81	52	1,230	680	404	190	193	3,300	1,720
	S	123	72	1,810	1,390	720	385	253	2,480	1,690

[1]Daily averages are for the 2-day period.

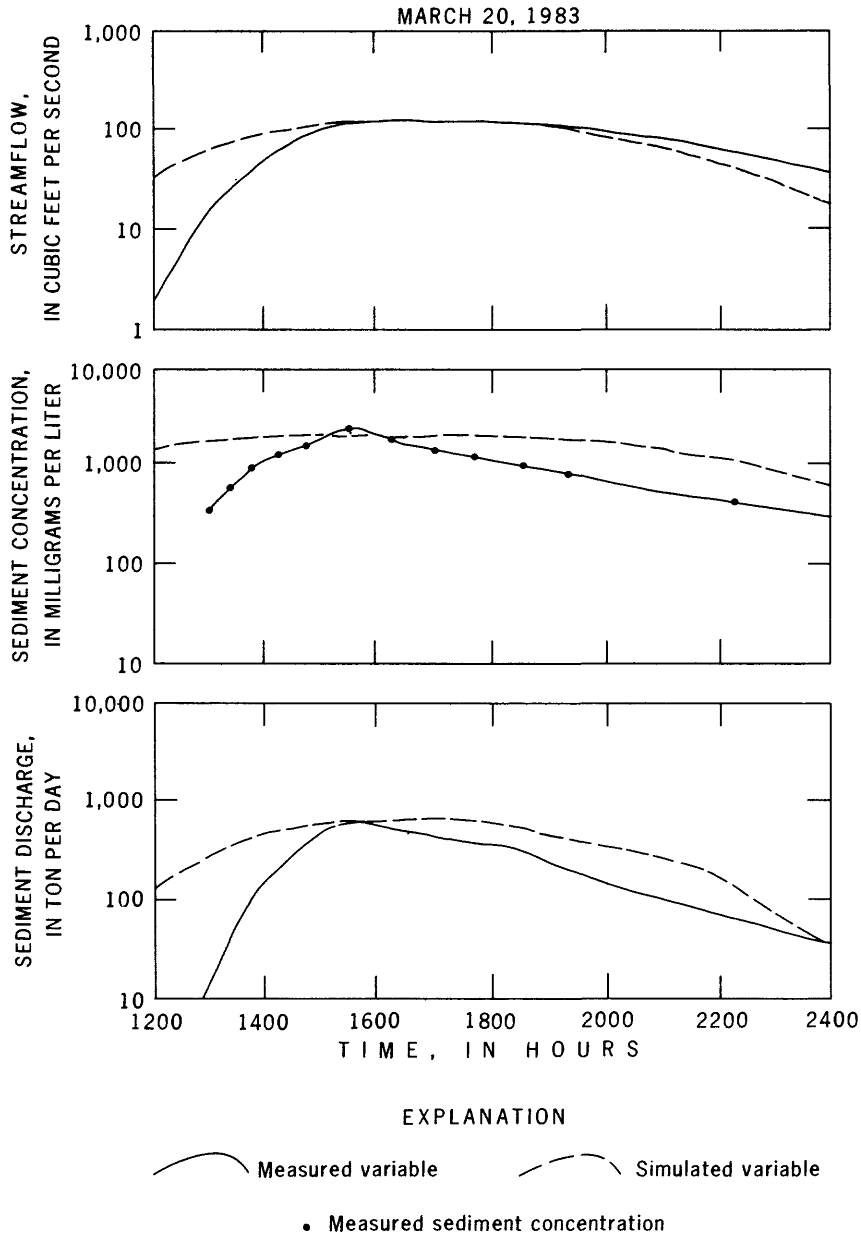

Figure 3.-- Measured values of streamflow, sediment concentration, and sediment discharge and values predicted during model verification.

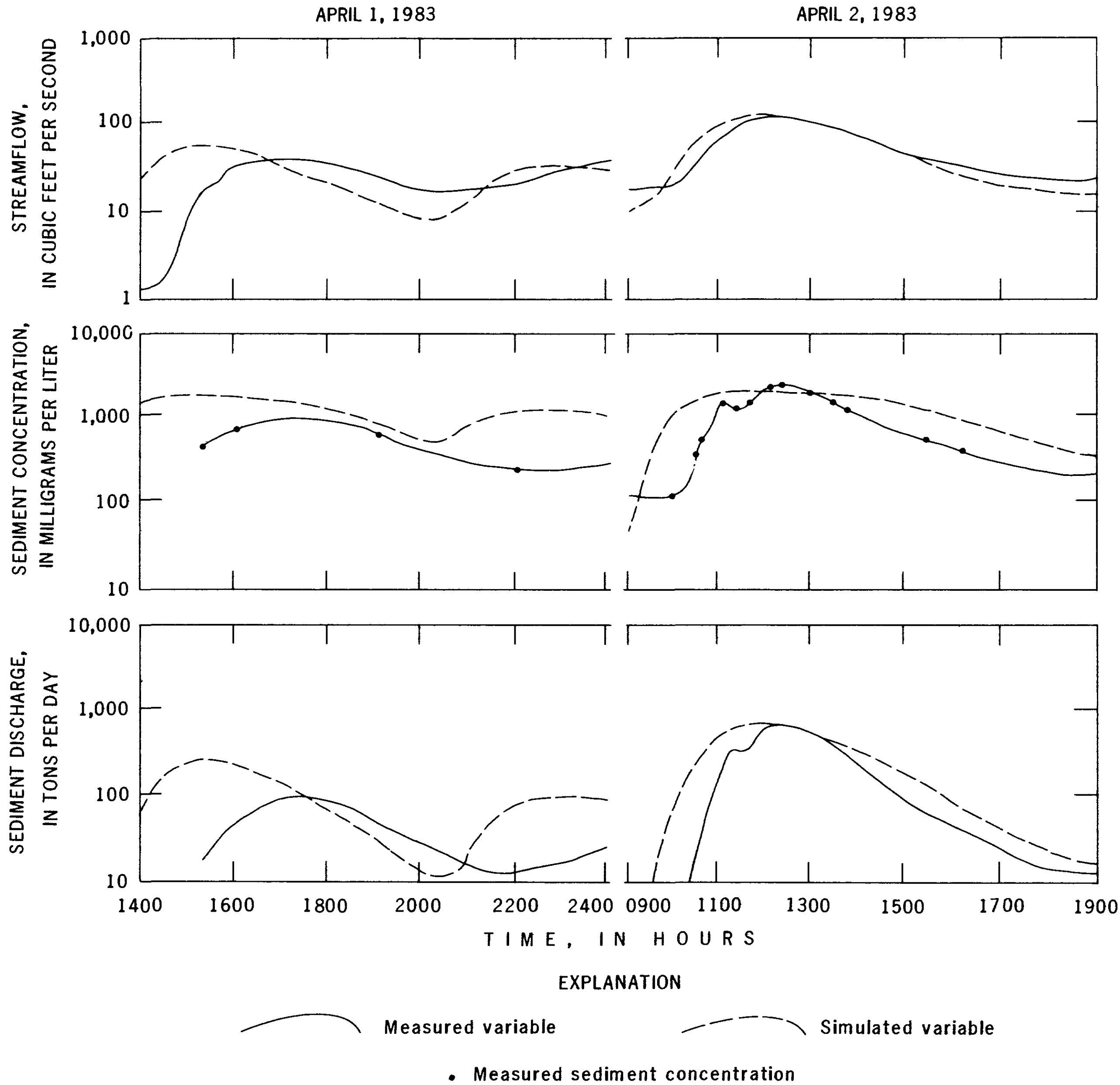

Figure 3.-- continued

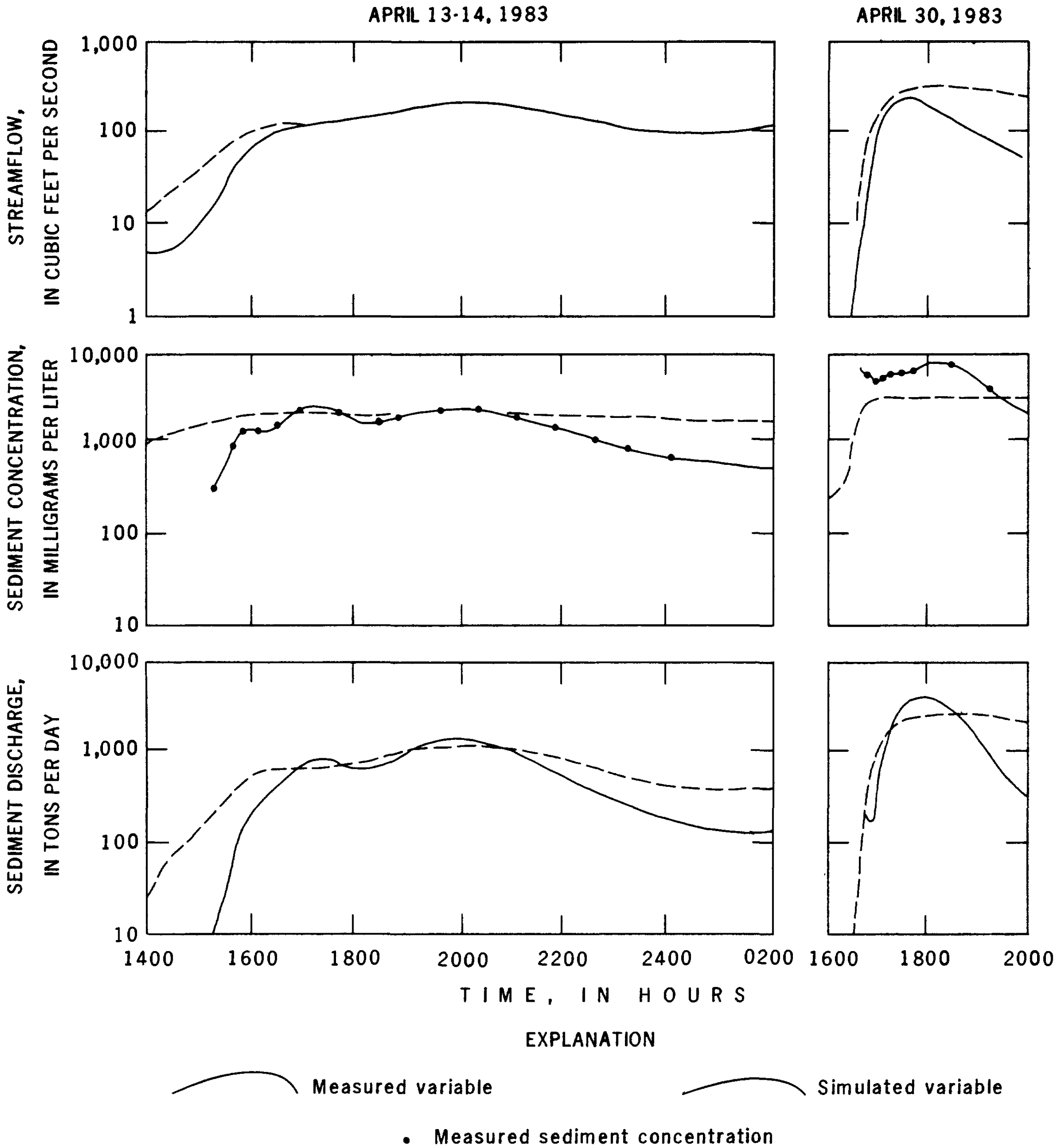

Figure 3.-- continued

The storms on April 30 and May 1 (May 1 hydrographs were not produced by ANNIE), 1983, had interesting runoff characteristics. Predicted streamflow was overly large for both storms, and predicted sediment concentration was too low for the storm on April 30 but overly large for the storm on May 1 (table 7). The unusual runoff characteristics may be related to the onset of cultivation in the watershed. No rainfall was recorded for about 2 weeks prior to the storm on April 30, and cultivation and seeding probably was done during this time because of the lack of rainfall. Because these activities disturbed the soil, sediment was scoured easily and rainfall infiltrated rapidly. Streamflow predicted by the model was overly large because infiltration capacity was not increased in the model when cultivation began. However, the predicted mean sediment concentration on April 30 (table 7) was too low because the potential for scour was not increased in the model to account for cultivation. For the storm on May 1 (table 7), the predicted streamflow was still too large but by only about 50 percent instead of by 100 percent as for the April 30 storm. The surface of the cultivated fields probably partly sealed after the rain on April 30. The seal decreased infiltration and increased measured streamflow to a rate similar to the simulated streamflow. The seal also decreased the potential for erosion. The low-intensity rainfall on May 1, which mostly was absorbed, further decreased erosion. Because the predicted amount of surface runoff was overly large during these storms and because of the sealing, the predicted sediment concentration for the storm on May 1 was too high. Although the model has the capability to make adjustments based on the degree of cultivation, those adjustments were not made during this study.

Error statistics are listed in table 8. Overall, the percentage error usually is less than that calculated for the calibration period. The smaller errors are associated with generally small, low-intensity storms. The mean streamflow for the storms used to verify the model is 89 ft^3/s (table 8), compared to 140 ft^3/s for the storms used to calibrate the model (table 5). The greatest improvement in percentage error during verification is in the maximum values. Percentage error for maximum streamflow, sediment concentration, and sediment discharge commonly is at least one-half that predicted during calibration.

The data for mean sediment concentration (table 8) can result in an inaccurate interpretation. The mean for all the mean sediment concentrations of the storms is about equal for the measured and simulated data. The bias, -31 mg/L, seems to indicate that measured mean sediment concentrations are slightly larger than the simulated mean. However, the individual mean sediment concentrations for storms in table 8 indicate that almost all measured mean concentrations for storms are smaller than simulated means. The mean for the storm on April 30, 1983 (table 8) is large enough to increase the overall mean for storms to a concentration almost equal to that of the simulated mean and to cause overall bias to be slightly negative.

Table 8.--Statistics from verification on error in simulated streamflow, sediment concentration, and sediment discharge for the duration of the storms

[ft^3/s, cubic feet per second; mg/L, milligrams per liter. Numbers in parentheses are the error term divided by the number on the same line in column 2, then multiplied by 100]

Statistic	Mean for all storms, measured statistic	Mean for all storms, simulated statistic	Mean absolute error for the averages of the simulated statistic (percentage of measured)	Root mean square error for the averages of the simulated statistic (percentage of measured)	Standard error of estimate for the averages of the simulated statistic (percentage of measured)	Bias for the averages of the simulated statistic (percentage of measured)
Average streamflow (ft^3/s)	89	123	35 (39)	60 (67)	62 (70)	34 (38)
Maximum streamflow (ft^3/s)	177	204	32 (18)	42 (24)	42 (24)	25 (14)
Mean sediment concentration (mg/L)	1,790	1,760	731 (41)	955 (53)	1,190 (66)	-31 (-2)
Maximum sediment concentration (mg/L)	3,450	2,320	1,130 (33)	1,910 (55)	1,920 (56)	-1,130 (-33)
Mean sediment discharge (tons per day)	611	786	175 (29)	199 (33)	117 (19)	175 (29)
Maximum sediment discharge (tons per day)	1,700	1,350	356 (21)	695 (41)	752 (44)	-349 (-21)

SUGGESTIONS FOR FUTURE STUDY

Modeling during this study indicated components of the model not yet tested and areas of the model that could be investigated further. The following is a list of activities that could evaluate and improve model accuracy.

1. The model could be tested using different rainfall, snowmelt, and runoff environments that have data sets sufficiently long to calibrate and verify the model adequately.

2. The effects of cultivation, surface sealing of soil, and freezing of soil could be simulated by varying infiltration, upper-zone nominal storage, and surface roughness during the simulation.

3. Methods for simulating infiltration rate during low-intensity storms could be investigated.

4. The dimensions of channel sections could be calculated using step-backwater or slope-area methods, and the improvement in simulated streamflow as a result of the calculations and data collection could be recorded. Also, the effect of changing the length of channel sections could be evaluated.

5. The size distribution of the suspended sediment could be analyzed, and the routing of sediment by particle size could be simulated.

6. The new algorithm for removing sediment from the land surface could be evaluated.

7. The reason for the small change in sand transport compared to large changes in the exponent and coefficient of the equation for transport in channels could be determined.

8. The sensitivity analysis could be expanded to include the effect of changes in LSUR, UZSN, and the number of RCHRES on the simulated discharge of sediment.

9. Several rain gages could be placed in the watershed to determine the number of rain gages needed to simulate streamflow and sediment concentration accurately.

10. The shear stresses at which detachment and settling of channel sediments begin could be determined.

11. Increasing the peaks of hydrographs for simulated sediment concentration could be attempted by increasing the washoff component of sedimentation and decreasing the rill erosion component.

SUMMARY AND CONCLUSIONS

The accuracy of the sediment-related algorithms in HSPF depends not only on the formulation of the algorithm but also on the accuracy of the rainfall, streamflow, and sediment record and on accuracy with which streamflow is simulated. Errors in recorded precipitation cause errors in simulated streamflow and sediment transport. Two problems in simulating streamflow were determined: (1) the beginning of simulated streamflow is sooner than that of measured streamflow; and (2) the rate of surface runoff simulated for low-intensity storms in the spring is overly large. As a result, the excess simulated surface runoff transported more sediment than actually was measured.

Hydrographs of simulated sediment concentration generally have smaller peaks and higher recessions than do the hydrographs of measured concentrations. A possible reason for the deviation of the simulated hydrograph of concentration from the measured hydrograph may be partly caused by the design of the channel system in the model. Sediment discharged into long channel sections is assumed to be immediately and completely mixed in the section. The assumption attenuates the simulated peaks and prolongs the simulated recessions. The addition of channel sections to increase the validity of the assumption decreases the accuracy of the simulation of streamflow.

Temporary changes in the land and stream-channel condition cause temporary changes in the relation of streamflow to sediment concentration. Measured sediment concentration was larger than simulated concentration for a late-winter storm in 1982, possibly because of an early season flushout of sediment that the model did not simulate. The model also did not accurately simulate sediment concentration for a storm in late April 1983. The predicted concentration was too low, possibly because the large measured sediment concentration was derived from sediment made available after cultivation during a dry period earlier in April.

Increased runoff from frozen soil caused the model predictions to be too low for streamflow and too high for sediment concentration during the winter. The infiltration capacity and erodibility of frozen soil is less than that for unfrozen soil. The model did not include these changes in soil condition and, therefore, simulated lower streamflow and higher sediment concentration than was measured.

The mean absolute error in simulated sediment concentrations during storms is 1,190 mg/L or 45 percent of the measured average. The error is caused by inaccuracies in the rainfall and streamflow record, in simulation of streamflow, and in simulation of sedimentation processes. These factors caused error at times during the year for the storms used for calibration.

The error analysis of the calibration data indicates that: (1) the largest errors, as a percentage of the measured mean were in predicting maximum streamflow and mean sediment discharge; (2) the smallest percentage errors are associated with small, low-intensity storms; and (3) errors, as a percentage of the measured average, changed randomly with the size of the storm.

Sediment yield is most affected by changes in the parameters for scour of soil by surface runoff. A 50-percent increase in the coefficient and exponent in the equation for scour increases sediment yield by 65 and 116 percent.

Storms used to verify the model occurred during the spring and mostly were of low intensity. As in calibration, the simulated hydrographs of sediment concentration have small peaks and high recessions compared to measured hydrographs of sediment concentration. Also, simulated sediment concentrations and discharges are somewhat larger than measured concentrations, probably because the volume of simulated surface runoff is overly large. Excessive simulated surface runoff in the calibration and verification storms of the spring increase simulated soil erosion and sediment concentrations and discharges.

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SUPPLEMENTAL DATA

The values of the calibrated parameters from HSPF that relate to streamflow and sediment transport are useful to other modelers. Therefore, tables 9 and 10 are provided. Data that relate stream depth, stream area, stream volume, and stream discharge for each stream channel section are provided in table 11. The sections are shown in figure 1.

Table 9.--Streamflow parameters used in the model

[in./hr, inches per hour; ft, feet; in., inches]

Parameter[1]	Value	Parameter	Value
INFILT	0.0045 in./hr	LSUR	350 ft
LZSN	6.0 in.	SLSUR	.016
INTFW	1.6	NSUR	.18
IRC	.30/day	DEEPFR	.0
AGWRC	.80/day	BASETP	.0
UZSN	.60 in.	AGWETP	.07

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
CEPSCM (in.)	0.01	0.01	0.02	0.02	0.03	0.04	0.04	0.04	0.03	0.02	0.01	0.01
LZETPM	0.02	0.02	0.07	0.16	0.25	0.38	0.45	0.45	0.35	0.18	0.08	0.02

[1]INFILT, infiltration parameter;
LZSN, parameter for lower zone nominal storage;
INTFW, parameter for interflow inflow;
IRC, parameter for interflow recession;
AGWRC, daily recession constant of ground-water flow;
UZSN, parameter for upper zone nominal storage;
CEPSCM, monthly capacity for interception storage;
LZETPM, monthly parameter for evapotranspiration from the lower zone.

Table 10.--Sediment-transport parameters used in the model

[lb/ft^2, pounds per square foot; lb/ft^2 x 5 min; pounds per square foot multiplied by 5 minutes]

Parameter[1]	Value	Parameter	Value
KRER	0.45	KSAND	1.0
JRER	2.5	EXPSND	1.0
SMPF	1.0	TAUCD for silt	.10 lb/ft^2
KSER	.06	TAUCS for silt	.16 lb/ft^2
JSER	1.5	M for silt	.05 (lb/ft^2) x 5 min
KGER	.15	TAUCD for clay	.08 lb/ft^2
JGER	1.3	TAUCS for clay	.19 lb/ft^2
AFFIX	.03	M for clay	.05 (lb/ft^2) x 5 min

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
COVERM	0.1	0.1	0.15	0.3	0.5	0.8	0.9	0.9	0.8	0.7	0.3	0.1

[1]KRER, the coefficient in the equation for detachment by rainfall;
JRER, the exponent in the equation for detachment by rainfall;
SMPF, the supporting management practice factor;
KSER, the coefficient in the equation for transport of detached sediment;
JSER, the exponent in the equation for transport of detached sediment;
KGER, the coefficient in the equation for scour by surface runoff;
JGER, the exponent in the equation for scour by surface runoff;
AFFIX, a parameter that causes a first-order rate of reduction of the amount of detached sediment because of reattachment to the soil;
KSAND, the coefficient in the equation for potential concentration of sand;
EXPSND, the exponent in the equation for potential concentration of sand;
TAUCD for silt, the shear stress at which silt begins to settle onto the streambed;
TAUCS for silt, the shear stress at which silt begins to scour from the streambed;
M for silt, the erodibility coefficient that determines the amount of erosion of silt from the streambed;
TAUCD for clay, the shear stress at which clay begins to settle onto the streambed;
TAUCS for clay, the shear stress at which clay begins to scour from the streambed;
M for clay, the erodibility coefficient that determines the amount of erosion of clay from the streambed;
COVERM, the fraction of the land surface for a given month covered from direct rainfall.

Table 11.--Stream depth, stream area, streamflow volume, and streamflow discharge for modeled channel sections

[ft^3/s, cubic feet per second]

Stream depth (feet)	Stream area (acres)	Streamflow volume (acre-feet)	Streamflow Discharge (ft^3/s)
		Reaches 1 and 2	
0.00	0.00	0.0	0.0
.20	.25	.03	.5
.40	.50	.11	3.0
.60	.75	.25	6.8
.80	1.01	.44	11.9
1.10	1.41	.83	22.3
1.60	2.01	1.76	46.5
2.00	2.50	2.73	70.4
3.00	3.77	6.15	148
4.00	5.05	11.0	249
5.00	6.15	17.1	372
6.00	7.50	24.5	515
7.00	8.80	33.6	750
8.00	9.90	44.0	1,250
9.00	11.3	55.0	1,400
		Reach 3	
.00	.0	.0	.0
.20	.50	.06	.5
.40	1.01	.22	3.0
.60	1.50	.50	6.8
.80	2.02	.88	11.9
1.10	2.82	1.66	22.3
1.60	4.02	3.52	46.5
2.00	5.01	5.46	70.4
3.00	7.54	12.3	148
4.00	10.1	21.9	249
5.00	12.3	34.2	372
6.00	15.0	49.0	515
7.00	17.6	67.2	750
8.00	19.8	88.0	1,250
9.00	22.6	110.0	1,400

Table 11.--Stream depth, stream area, streamflow volume, and streamflow discharge for modeled channel sections--Continued

Stream depth (feet)	Stream area (acres)	Streamflow volume (acre-feet)	Streamflow Discharge (ft^3/s)
		Reach 4	
0.00	0.0	0.0	0.0
.20	.46	.05	.5
.40	.92	.18	3.0
.60	1.38	.41	6.8
.80	1.84	.74	11.9
1.10	2.53	1.39	22.3
1.60	3.68	2.94	46.5
2.00	4.60	4.60	70.4
3.00	6.90	10.4	148
4.00	9.20	18.4	249
5.00	11.5	28.8	372
6.00	13.8	41.4	515
7.00	16.1	56.4	750
8.00	18.4	73.6	1,250
9.00	20.7	93.2	1,400
		Reach 5	
.00	.0	.0	.0
.20	.62	.07	.5
.40	1.26	.28	3.0
.60	1.88	.62	6.8
.80	2.52	1.10	11.9
1.10	3.53	2.08	22.3
1.60	5.03	4.40	46.5
2.00	6.26	6.83	70.4
3.00	9.43	15.4	148
4.00	12.6	27.4	249
5.00	16.9	51.2	372
6.00	20.7	73.6	515
7.00	24.2	101.0	750
8.00	27.3	132.0	1,250
9.00	31.3	165.0	1,400
10.00	35.3	198.0	1,550

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