An Analysis of Some Storm-Period Variables Affecting Stream Sediment Transport

By H. P. GUY

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

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AN ANALYSIS OF SOME STORM-PERIOD VARIABLES AFFECTING STREAM SEDIMENT TRANSPORT

By H. P. GUY

ABSTRACT

This study of the effect of some natural factors on storm-period fluvial-sediment transport is a part of the development of techniques for utilization of sediment reconnaissance data. In more general terms, this report presents a study of the time and space variation of sediment transport in streams.

A review of the theory of sediment yield and transport indicates that for most streams the bulk of the suspended sediment transport occurs during the relatively brief storm periods when the drainage basin collects and routes precipitation excess to a specific site. Therefore, a description of the quantity of sediment moved during the storm runoff periods at a stream location must be based principally on the active and passive forces of erosion.

The investigation of these forces was accomplished by using a combination of graphical and analytical multiple correlation techniques. Graphical correlation was employed on data for seven stream locations in the Atlantic coast area; first, to determine which climatic, hydrologic, and sedimentologic variables might be used; second, to determine the required transformation of data; and third, to note any unusual elements of data or wild points for specific variables. An analytical method using the general multiple regression model on the electronic computer was then employed to develop and indicate the accuracy of optimum equations for predicting sediment movement with surface runoff. Several combinations of variables for each stream location were used to show the effect of interdependence among the variables.

In regard to a choice of the dependent variable for defining sediment variation, the mean concentration of sediment in streamflow was found to be somewhat superior to sediment discharge due to the high degree of intercorrelation between water discharge and sediment discharge.

Some of the storm-to-storm variation of sediment concentration in streamflow was found to be associated with storm magnitude, the time during a period of record, the season of the year, the antecedent condition of the basin, and the storm intensity. The sediment moving in streams tends to increase with measures of storm magnitude such as surface runoff quantity or rainfall quantity. An apparent trend of decreasing sediment with time was indicated for the records of all seven locations, but was statistically significant only for the locations on the Brandywine Creek and the James River basins. With respect to seasonal change, sediment concentration tends to increase as mean air temperature increases. With respect to antecedent condition, sediment concentration tends to decrease as ground-water runoff increases. Ground-water runoff is generally high during the cool season for the Atlantic coast area; therefore, intercorrelation with mean air temperature reduces the importance of this variable. Sediment concentration was found to increase with storm intensity. The measures of storm intensity used were peakedness index, peak flow, and rainfall intensity; however, only peakedness index was tested for all streams.

The standard error of estimate of the dependent variable (the storm-period sediment concentration) ranged from 0.14 to 0.30 log units for most combinations of the independent or causative variables mentioned above. The range of this error was greater among the different streams than among the different combinations of variables for a given stream. This is attributed to variance of hydrologic and environmental factors that are not evaluated by the data, or possibly by the effect of some measurement errors in the basic data.

Three of the regression formulas derived in the above analysis were tested for extrapolation to other areas using observed data from the Shenandoah and Potomac Rivers. The results showed that these formulas can and must be modified to give a satisfactory comparison with the observed data.

INTRODUCTION

The development of methods for more effective use, and understanding, of available and future fluvial-sediment data is considered to be the principal objective of this study. Sediment stations on streams are widely scattered or nonexistent in many areas because of (1) the high cost of sediment-measuring programs, (2) inadequate interpretation of the data, and (3) rather poor recognition of the need for sediment knowledge. Knowledge of stream-sediment conditions is so meager in many places that effective fluvial-sediment measurement programs cannot be designed satisfactorily without first making some reconnaissance measurements. Kind and intensity of such required reconnaissance observations must be based on knowledge of sediment conditions in distant as well as nearby streams and of the applicable techniques for interpreting the data. The study should also advance progress toward development of a "universal equation" for computing the magnitude of stream sediment transport by application of observations to specific variables.

Sediment transport in a stream depends on such a great variety of circumstances that it is not considered practical to define fixed laws that would indicate the rate and amount of such sediment transport in the stream at any specific location. More specifically, the effects of widely varying climate, vegetation, and soils cause sediment conditions in streams to vary widely in time and space. Therefore, the task of describing and interpreting the yield, character, transport, and deposition of fluvial sediment seems almost insurmountable. In the past the most common method for describing fluvial sediment has been to collect a body of seemingly basic data representing the conditions of the problem requiring solution. Nearly all these data have been interpreted only so far as required for solution of the problem at hand, leaving the broader implications untouched. These programs have resulted in the basic data being widely scattered or even nonexistent in most parts of the country. This widely scattered information, however, could be a reservoir of data that if properly interpreted would increase general knowledge of fluvial sediment characteristics.

Therefore, the purpose of the project was to develop principles and methods for better understanding and use of sediment data. Experience has shown that it is not practical to describe sediment conditions in time and space with a comprehensive sampling program involving vast quantities of basic-sediment data. It may be practical, however, to use a limited amount of basic data and a program of data analysis and interpretation based on knowledge from adjacent areas. It is expected that the principles and methods will indicate the kind of measurements of environmental factors that can reasonably be obtained for interpretation of the sediment data.

The author acknowledges with warm appreciation the helpful suggestions and criticisms from colleagues who assisted in the formulation of the project, provided technical guidance, and read an early draft of the manuscript. Particular thanks are extended to W. F. White, W. B. Langbein, R. B. Vice, P. C. Benedict, B. R. Colby, B. C. Colby, and D. W. Hubbell. Messrs. F. J. Keller and H. E. Reeder assisted in assembly of data and correlation of variables for the Scantic and James River basins, respectively.

SCOPE OF WORK AND AVAILABLE INFORMATION

The scope of the work involved to meet the objective of developing principles and methods for better understanding and use of sediment data is limited to a considerable extent by the availability of sediment and environmental data. Hence, it is necessary to determine what correlative, mathematical, and "intuitive" techniques can be developed to give substance and understanding to this limited supply of available data.

The analysis of the available data for this report is limited to the Atlantic coast area. The bulk of the sediment data consists of daily mean concentration and daily suspended-sediment discharge at 39 sites in several river basins as indicated by the records listed in table 1. These records of sediment data were determined from the results of depth-integrated samples mostly taken at a single fixed stream vertical and adjusted, if necessary, by use of more complete definition of concentration in the stream cross section. Samples generally were taken once per day, except during periods of rapidly changing water discharge or sediment concentration. During these changing conditions the aim was to make several observations per day. When sufficient samples could not be obtained during the changing conditions to define the nature of concentration variation during the storm-runoff event, simple statistical methods were used to arrive at a computed or estimated value of the concentration.

TABLE 1.—*Daily suspended-sediment records to September 1960 for streams draining to the Atlantic Ocean from the United States*

[Dates marked with an asterisk indicate record still in progress September 1960]

Stream and location	Drainage area (sq mi)	Month and year of record
Scantic River at Broad Brook, Conn	98.4	*11/52
Kayaderosseras Creek near West Milton, N.Y	90	3/53–7/55
Mohawk River at Cohoes, N.Y	3,456	1/54–6/59
Stoney Brook at Princeton, N.J	44.5	*1/56
Delaware River at Port Jervis, N.Y	3,076	2/57–9/58
Lehigh River at Walnutport, Pa	889	5/48–3/53
Delaware River at Trenton, N.J	6,780	*9/49
Schuylkill River at Port Carbon, Pa	27.1	2/49–6/51
Schuylkill River at Landingsville, Pa	133	9/47–3/53
Schuylkill River at Auburn, Pa	160	9/47–6/51
Schuylkill River at Berne, Pa	355	*9/47
Schuylkill River at Pottstown, Pa	1,147	3/48–9/51
Little Schuylkill River at South Tamaqua, Pa	69.4	4/50–4/53
Little Schuylkill River at Drehersville, Pa	122	9/47–6/51
Perkiomen Creek at Gratersford, Pa	279	4/48–3/53
Schuylkill River at Manayunk, Philadelphia, Pa	1,893	*10/47
Brandywine Creek at Wilmington, Del	314	*12/46
Corey Creek near Mainesburg, Pa	12.2	*5/54
Elk Run near Mainesburg, Pa	10.2	*5/54
Susquehanna River at Towanda, Pa	7,797	1/51–7/54
North Bald Eagle Creek at Milesburg, Pa	265	12/55–3/58
Bald Eagle Creek at Blanchard, Pa	339	12/55–3/58
Marsh Creek at Blanchard, Pa	44.1	11/55–3/58
Juniata River at Newport, Pa	3,354	1/51
Bixler Run near Loysville, Pa	15.0	*2/54
Swatara Creek at Harper Tavern, Pa	333	*5/59
Shenandoah River at Front Royal, Va	1,638	4/53–9/56
North Fork Shenandoah River near Strausburg, Va	772	10/55–9/56
Hazel River at Rixeyville, Va	286	10/51–9/55
Rappahannock River at Remington, Va	616	*4/51
Rapidan River near Culpepper, Va	465	5/51–9/56
James River at Buchanan, Va	2,084	5/51–9/56
James River at Scottsville, Va	4,571	12/50–9/56
Roanoke River at Altavista, Va	1,802	2/53–9/56
Roanoke River at Randolph, Va	3,000	1/54–6/57
Dan River at Paces, Va	2,550	1/54–6/57
Tar River at Tarboro, N.C	2,140	*1/58
Yadkin River at Yadkin College, N.C	2,280	*1/51
South Yadkin River near Mocksville, N.C	313	*1/58

The variation found in sediment conditions, among sites and with time, indicates that most records of less than 4 years do not define the sedimentologic conditions of the stream within acceptable limits. This is caused by the highly variable meteorologic and cultural patterns acting on the drainage basin which affects the sediment transported in the surface runoff. Thus when sediment data are collected only for a few storms in one season, the results are considered to be reconnaissance information.

Table 1 shows that most of the data for the Atlantic coast area are from a few States; thus, further indicating the need for developing techniques to extend available sediment data. Furthermore, even though Pennsylvania has the greatest number of station-years of record, the data represents only a small percentage of the drainage area in this particular State. Also, the special sediment studies in the Schuylkill River basin are demonstrative of the fact that stations on large drainage basins do not give information as to the various conditions in that particular basin. On the other hand, the small area stations represent only some of the environmental conditions. The overall result is that, although the 39 stations listed in table 1 seem to represent a lot of information, the deficiency of sediment knowledge is still very great.

The development of the principles and methods used in this report is based on aspects of hydrology and sedimentology discussed in the following sections, entitled "Theory of sediment yield and transport" and "Storm characteristics."

THEORY OF SEDIMENT YIELD AND TRANSPORT

The two principal components of natural streamflow for eroding and transporting sediment are the surface or overland flow resulting from precipitation excess and the base flow from springs and other ground-water seepage. The sedimentological aspects of these segments of hydrology stem from the erosion and transportation capacity of the overland flow as it makes its way to stream channels by way of sheet and rill flow and (or) from the transporting and bank-eroding power of high streamflow which may be derived from large quantities of ground-water flow.

Overland runoff, as determined from precipitation excess, is the most active agent causing erosion and sediment transport. Thus rainfall intensity and infiltration capacity at the land surface are important factors affecting the amount of sediment movement. Both these factors are known to vary greatly with time and location within a drainage basin. The precipitation generally ranges from a light drizzle during the cool season to a heavy downpour during the warm summer months. The infiltration ranges from zero through impermeable surfaces to several inches per hour through a forest floor with good duff and a very permeable subsoil.

FINE SEDIMENT

SPLASH, SHEET, AND RILL EROSION

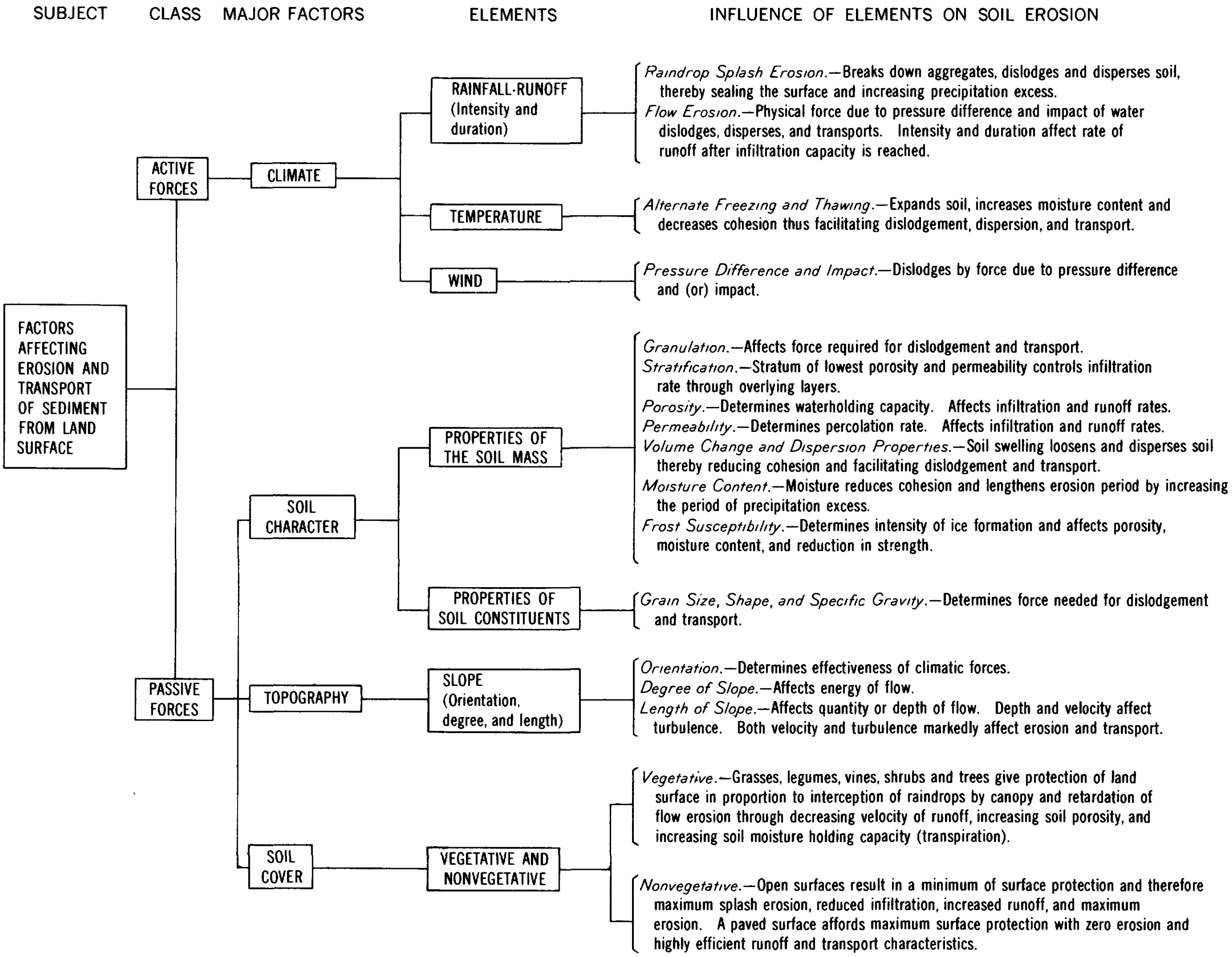
On land surfaces of erodible sediment, the kinetic energy of the raindrops causes a large amount of splashing of the soil and water and, hence, transport of fine sediment in two ways. First, is the net movement in a downslope direction by gravity and (or) in the leeward direction by wind as it is briefly airborne. Second, is that the impact of rainfall and dispersion of soil particles cause a sealing of the soil surface thereby reducing the infiltration. The reduced infiltration increases the amount of precipitation excess that must make its way to stream channels carrying its load of eroded sediment. This movement of flow over the land before collecting in the rills is called sheet flow. The reduced infiltration is effective in increasing the amount of flow in the rills and stream channels and thereby the erosive power in these channels is also increased.

The way in which sheet flow differs from rill and channel flow in eroding and transporting sediment is considerable. Sheet flow moves rather slowly owing to the small amount of tractive force (small depth) and owing to the large amount of resistance (relative roughness) offered by the land surface. The rill and channel flow, on the other hand, is confined to a small area of resistance; and with its relatively great depths and hence large tractive force or gravity potential, the energy of flow concentrated in a small area can be sufficient to move sand, gravel, or even boulders. Sheet flow therefore erodes and transports fine-grained sediment, the silts and clays, whereas the rill and other types of concentrated channel flow will carry all the fine-grained load derived from this sheet flow in addition to both fine and coarse sediments that may be eroded from the bed and walls of the channels.

Thus, it is evident that the quantity of fine sediment moved by the stream at a given time is nearly equal to that released by the environmental factors causing erosion within the drainage basin; whereas, the quantity of the various coarser sizes in transport is closely related to the magnitude of the fluid forces. For coarse material, Lane (1955) reported that if the supply is not equal to the carrying capacity through a stream reach, the stream will aggrade or degrade to establish approximate equilibrium between capacity and discharge of coarse sediment within the reach.

ENVIRONMENTAL FACTORS

Only small and generally unrelated segments of the relation of environmental factors to fluvial sediment have been studied by hydrologists and sedimentologists because of the diversity of climatic conditions, geographic areas, and segmented problem-solving objec-



Raindrop Splash Erosion.—Breaks down aggregates, dislodges and disperses soil, thereby sealing the surface and increasing precipitation excess.

Flow Erosion.—Physical force due to pressure difference and impact of water dislodges, disperses, and transports. Intensity and duration affect rate of runoff after infiltration capacity is reached.

Alternate Freezing and Thawing.—Expands soil, increases moisture content and decreases cohesion thus facilitating dislodgement, dispersion, and transport.

Pressure Difference and Impact.—Dislodges by force due to pressure difference and (or) impact.

Granulation.—Affects force required for dislodgement and transport.

Stratification.—Stratum of lowest porosity and permeability controls infiltration rate through overlying layers.

Porosity.—Determines waterholding capacity. Affects infiltration and runoff rates.

Permeability.—Determines percolation rate. Affects infiltration and runoff rates.

Volume Change and Dispersion Properties.—Soil swelling loosens and disperses soil thereby reducing cohesion and facilitating dislodgement and transport.

Moisture Content.—Moisture reduces cohesion and lengthens erosion period by increasing the period of precipitation excess.

Frost Susceptibility.—Determines intensity of ice formation and affects porosity, moisture content, and reduction in strength.

Grain Size, Shape, and Specific Gravity.—Determines force needed for dislodgement and transport.

Orientation.—Determines effectiveness of climatic forces.

Degree of Slope.—Affects energy of flow.

Length of Slope.—Affects quantity or depth of flow. Depth and velocity affect turbulence. Both velocity and turbulence markedly affect erosion and transport.

Vegetative.—Grasses, legumes, vines, shrubs and trees give protection of land surface in proportion to interception of raindrops by canopy and retardation of flow erosion through decreasing velocity of runoff, increasing soil porosity, and increasing soil moisture holding capacity (transpiration).

Nonvegetative.—Open surfaces result in a minimum of surface protection and therefore maximum splash erosion, reduced infiltration, increased runoff, and maximum erosion. A paved surface affords maximum surface protection with zero erosion and highly efficient runoff and transport characteristics.

FIGURE 1.—Chart of the principal factors affecting erosion and transport of sediment from the land surface. Modified from Johnson (1961).

tives. Interpretation of this relation, using limited data for some specific climatic and drainage basin characteristics are reported by Glymph (1954), Maner (1958), Langbein and Schumm (1958), and Stall and Bartelli (1959). The sum of these and other works compose a meager knowledge of the total relation of environment to fluvial sediment.

Sayre, Guy, and Chamberlain (1962) listed five factors affecting the supply of sediment moved into and through a stream channel and, most applicable, the fine material contributed from the drainage area. This list, which follows, expands on the broad terms of climate and physical characteristics:

1. The nature, amount, and intensity of precipitation.
2. The orientation, degree, and length of slopes.
3. The geology and soil types.
4. The land use.
5. The condition and density of the channel system.

They noted also that these factors can operate either, or both, to resist or to advance the rate of erosion and transport. Precipitation, for example, if occurring at a low intensity and at ideal intervals, may advance the growth of vegetation and thereby the resisting force. Precipitation, if intense and following a drought, or occurring on an area without vegetative cover, is likely to cause a large amount of erosion. Because of the large variance and interrelation associated with the preceding list of factors, the definition of erosion and transport in drainage areas is difficult to attain.

One important factor resulting from the integrated effect of the above five factors is that the sediment yield of a large basin is generally found to be less than the sum of its subbasins. For example, the yield from a drainage area of 5 square miles generally ranges from 400 to 4,000 tons per square mile; whereas, for 500 square miles the range is 100 to 2,000 tons per square mile (Glymph, 1951). Though the deviation of yield for a given size of basin is very great, the trend implies that sediment yield decreases as drainage area increases. For streams in equilibrium and having a fixed base level at the mouth, this loss of sediment in a stream system may be temporary. On the other hand, if the oceans are gradually rising with respect to the stream system, or a system of manmade base levels is imposed, the loss of sediment may be accounted for by the aggradation of the streams. Such sediment loss or aggradation also occurs when accelerated erosion in a drainage basin supplies more sediment than can be transported by the channel system. An index of the phenomenon of decreasing sediment in the downstream direction may at some future time be evaluated through some index of the condition and density of the channel system.

The interrelations of the active and passive forces that influence erosion are summarized in figure 1, as modified from Johnson (1961). Climate is considered the important active force as determined by rainfall, temperature, and wind. The important passive forces are the soil character (properties of soil mass and constituents), the topography (orientation, degree of slope, and length of slope), and the soil cover (vegetative and nonvegetative). Each of the active and passive forces are further described by refined factors in the illustration. For example, rainfall has a double action—first is that of falling raindrops as described in a preceding paragraph and second is that of flowing water, which in broad terms is of either laminar or turbulent flow. The type of flow is a function of the velocity and depth of the water and the roughness of the surface over which it flows. Erosion and transport of sediment are negligible under the condition of laminar flow but, as the water from such laminar flow collects in rivulets and larger channels, the resulting energy of flow with increased scale and intensity of turbulence can be sufficient to carry heavy loads of sediment, especially fine particles. The important passive forces, therefore, tend to alter the depth and velocity patterns of overland or surface flow by keeping the flow spread thinly or by increasing the resistance to flow.

COARSE SEDIMENT

EFFECT OF VELOCITY

B. R. Colby (written communication) showed that the discharge of sand in a sand-bed stream is closely related to the mean velocity of flow for rivers of a wide range of sizes. Many investigators had previously used the supposedly logical parameter of stage or depth as the independent variable for determining sand transport. The fallacy of the depth-transport concept is that the relation between velocity and depth has been demonstrated by Dawdy (1961) to be poorly defined both for an individual stream and among streams. Colby (1961) illustrated the complexity of the depth-transport concept by showing that the transport decreases with increasing depth at low velocity (less than about 3 fps (feet per second) and increases with increasing depth at high velocity.

Einstein (1950) treated the beginning of movement and the pickup of the sand grains from the bed as a probability for the individual grains to move. Thus a specific critical velocity is probably arbitrary and inexact as a measure of bed movement because of the arrangement of the grains on the bed and on local variations of velocity. At a velocity greater than the so-called critical value, movement in a very thin layer occurs by rolling, sliding, or skipping along the bed.

Sand swept up from the bed of a natural stream or suspended in a stream may be supported and transported downstream a considerable distance by the vertical components of currents in turbulent flow. The magnitude of these currents is largely a function of the horizontal velocity, the bed roughness, and the distance above the streambed. Hence, the suspended load of sand in a stream vertical can be considered to be associated with the mean velocity of flow.

EFFECT OF PARTICLE SIZE

The settling rate of a particle is a measure of its resistance to transport. Fine sediment particles in a dispersed state having a slow settling rate are easily carried in complete suspension by the fluid forces in natural streams, and, hence, have a tendency to move out of the drainage basin with the flow in which they are suspended. In contrast, coarse sediment particles with a fast settling rate may move by suspension for only short distances, or more probably, by rolling and bounding along the streambed. The smaller of these coarse particles move at a faster mean velocity than do the larger particles. The largest particles in a given stream would be transported only a short distance in a given period of movement and then only when the stream is experiencing a great flood. The coarse sediments on or near a streambed are being continuously sorted by the selective transport capacities of the stream.

Equilibrium of the concentration gradient of suspended sediment at a stream vertical requires that particles settling through a plane be balanced with a net upward movement of particles through this plane from a zone of heavier concentration. Particle fall velocity is then considered to be an indication of the rate of change of sediment concentration with distance above the streambed for a given scale and intensity of turbulence. An increase in turbulence, considered to mean an increase in the vertical movements of flow, causes more uniformity of concentration for a specific size of sediment with respect to distance above the bed. Therefore, high values of velocity and (or) low values of particle size tend toward a uniform vertical concentration of sediment. If mean velocity is an indication of the scale and intensity of turbulence and the vertical variation of sediment concentration, then the discharge of coarse sediment is related to both stream velocity and particle size.

Colby (1961) showed that for a given mean velocity and a roughly equal bed roughness, a stream at a section of shallow depth will result in greater turbulence and hence contain a higher concentration of suspended coarse particles in a vertical than will be found in a deep section of the stream. Averaged over a long period of time, the sediment transported at the two sections, even though several hundred feet apart, is likely to be equal. With a substantial change of flow characteristics, such as greater depth and velocity, the transport through the two sections may temporarily be different, causing aggradation or degradation of the streambed.

The laboratory studies by Simons, Richardson, and Haushild (1962) showed inconclusive results regarding the effect of increasing concentration of fine material on the transport of coarse sediment. The data support the conclusion, however, that if bed roughness were the same, increasing fine sediment concentration will increase the transport of coarse sediment because the mean velocity of flow may be increased and the fall velocity of sediment particles may be decreased due to changes in the apparent viscosity and density of the suspending fluid.

Water temperature is an important environmental factor affecting the transport of sediment through its effect on viscosity of the fluid and the resulting changes in the fall velocity of the particles and changes in the turbulence of the streamflow. The effect of change in water temperature on particle fall velocity is greatest for fine sediment because these sizes settle more nearly in accordance with Stokes' law. For example, particles in a size class of 0.016–0.062 mm have a fall velocity of about 0.0017 fps at 32°F and 0.0038 fps at 90°F; whereas, particles in a class of 1.00–2.00 mm have a fall velocity of 0.59 fps at 32°F and 0.74 fps at 90°F (Hubbell and Matejka, 1959). Temperature change, however, does not affect the transport of fine material (less than 0.062 mm) because it is limited by the amount supplied to the stream system; that is, the stream will readily carry all available fine sediment at either a high or a low temperature. The temperature effect is probably most important for fine and medium sizes of sand.

STORM CHARACTERISTICS

Precipitation is undoubtedly one of the most important and yet most complex factors associated with the erosion and transport of fluvial sediment. A wealth of data concerning precipitation characteristics has been obtained by the U.S. Weather Bureau since 1891. The basic precipitation data, daily quantity for nonrecording gages and hourly quantity for recording gages, is published in "Climatological data" by the Bureau. This data has been recorded for 40 to 50 years. The density of the gages in the Atlantic coast area averages about 2.5 per 1,000 square miles for the nonrecording gages and 0.9 per 1,000 square miles for the recording gages. This seemingly large number of gages gives a fair representation of precipitation over large river basins, especially for storms of large aereal extent but are very inadequate when correlation with small basins is necessary, especially for the small convection storms.

Wischmeier and Smith (1958), in a correlation of rainfall characteristics with erosion and soil loss data, showed that an index consisting of the product of rainfall energy and the maximum 30-minute intensity of the storm is the most important measurable precipitation variable to explain storm-to-storm variation of soil loss from field plots. This concept is based on the fact that large fast-falling raindrops with a large amount of kinetic energy will cause much splash erosion, thereby sealing the surface and increasing the amount of surface runoff. The maximum 30-minute intensity is also proportional to both the total quantity of rainfall and the average intensity.

THE RUNOFF HYDROGRAPH

Storm runoff is defined as the part of total runoff derived from storm rainfall or rapid snowmelt which reaches an observation point within a relatively short period of time. The time of runoff depends on the drainage basin characteristics, especially that of area, and requires only a few minutes for areas of a few acres but 5–12 days for drainage areas of 10,000 square miles. The ground water runoff or base flow part of a streamflow hydrograph lags the causative precipitation by a distinguishably longer period of time than does the surface runoff. Oftentimes, storm runoff may include subsurface ground-water flow which has infiltrated the surface of the ground but causes an increase in ground-water flow to the surface channel sufficiently soon to be classed as storm runoff. Such rapid transit of the subsurface storm flow results from the relatively short underground path through perched water tables, through flowing saturated zones, or through semichannels beneath the surface. The true

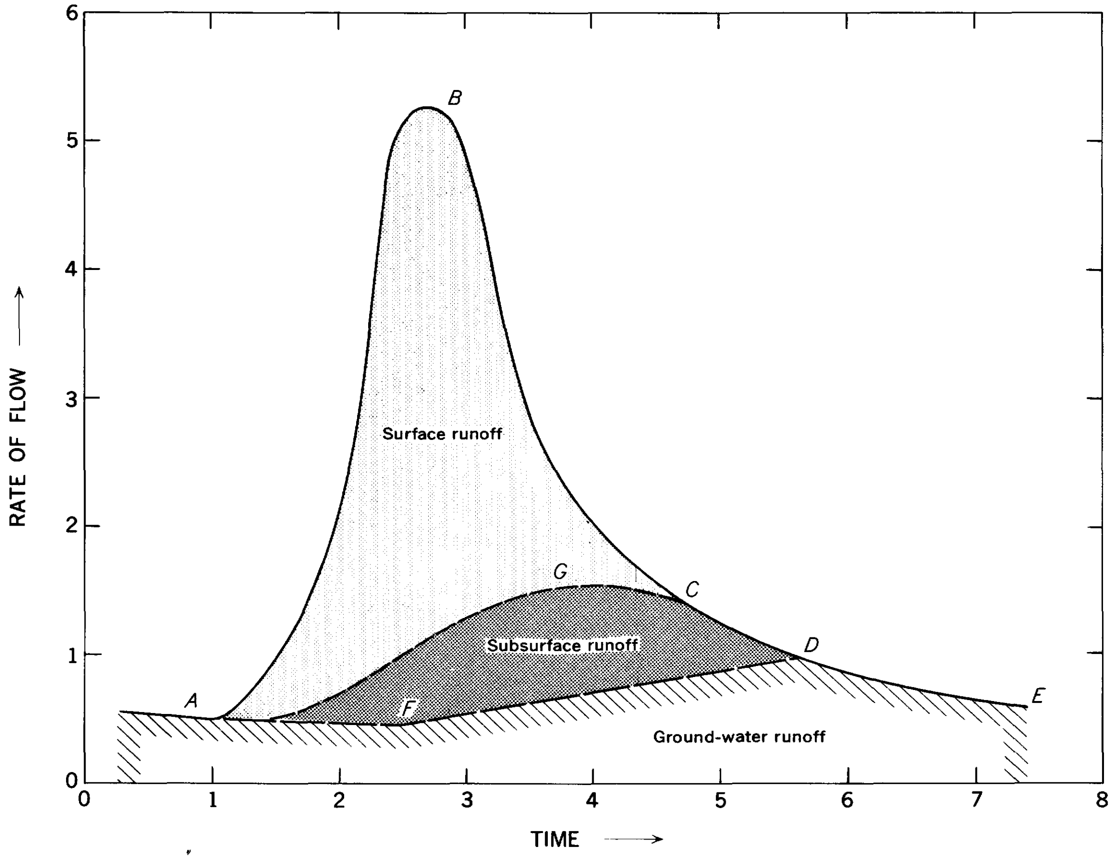


FIGURE 2.—Components of a streamflow hydrograph.

surface runoff, or that amount of precipitation in excess of infiltration and surface storage, reaches a surface channel with its path on and above the ground surface. Except for ephemeral streams and small plots or fields, the physical measurement of these separate components of flow is practically impossible.

Attempts to separate storm runoff into the components of surface and underground runoff are made primarily through empirical analysis of runoff hydrographs. The general concepts of such an analysis are illustrated by figure 2, showing a typical hydrograph where *ABCDE* represents the total runoff, where *AFDE* represents the amount of ground-water runoff, and where *AGC* is the estimated division line between true surface runoff and subsurface runoff. The area between curves *AGC* and *AFD* represents the volume of subsurface flow effected by the storm. The division line *AGC*, separating the surface and underground runoff, is of greatest significance in this study since the amount of sediment erosion in the upland areas should logically be directly related to only the amount of surface runoff. The transport rate of the coarser sizes of sediment in the stream channels is affected by the total flow.

Since water discharge generally varies directly with gage height at a given stream site, it is feasible to use the trace of the gage-height recorder instead of plotting the water discharge against time to separate the components of surface and underground runoff. In fact, more sensitive results are possible by use of the gage-height chart because the line represents nearly instantaneous conditions, whereas most discharge data are averages for discrete elements of time. The writer has not found it convenient, however, to obtain and use the gage-height records in most instances.

The most convenient hydrographic data source for investigating records of considerable length is the series of Water-Supply Papers, "Surface Water Supply of the U.S.," which give the mean flow for each day of all streams gaged. With the exception of the low-yield storms, the author has also found that a tabular system using these daily values is quite adequate to separate the components of surface and underground runoff. Fortunately, the errors involved in estimating the volume of underground runoff are generally small in comparison with the volume of total surface runoff. For low-yield storms, where the amount of underground flow is more significant relative to the total flow, the number of days involved in the hydrograph will be fewer and hence the chance of significant cumulative error will be less.

SEASONAL CHARACTERISTICS

PRECIPITATION

The air always contains some water vapor, but rain or snow occurs only a small part of the time. Precipitation requires, in addition to moist air, and atmospheric disturbance in the air mass through lifting of large volumes of warm moist air to higher altitudes where it is cooled to a temperature below the dew point. Although the lifting is the decisive factor, strong convergence is also necessary to produce heavy precipitation. On the basis of the meteorological phenomena that cause and accompany precipitation, the causative storms may be divided into three types, namely, cyclonic, convectional, and orographic.

The contrast of the large land and water masses of the earth causes differential heating from the sun and therefore a great impetus for circulation of air. For example, in the winter the landmass cools more rapidly and may be covered with snow which reflects much of the sun's heat rather than absorbing it. High pressure cells of cold then push the polar front toward the south in North America. Low pressure cells of warm air are formed over adjacent ocean areas at this time. In the summer this situation is reversed.

Cyclonic storms are atmospheric waves, formed along the polar front by the interaction of the cold and warm airmasses. The general circulation pattern caused by the earth's rotation, or the terrestrial winds, pushes these storms from west to east in the latitude of the United States. Such cyclonic storms are characterized by a warm moist air sector on the south side which, being lighter than the existing cool air it meets, rides up over the wedge of cool heavy air. This causes condensation and a broad belt of rather low-intensity and long-duration precipitation when a warm front is experienced and a belt of rather high-intensity and short-duration precipitation when a cold front is experienced. The cold front moves more rapidly and has a steeper gradient of cold air than does the warm front.

The convectional type of storm is caused by uneven heating over a relatively small area and occurs only in areas of the large low pressure cells of warm air. For example, convection may be triggered by excessive heating of the air over a city when the streets and roofs are warmer than the surrounding countryside. The ascending warm air expands and cools as it rises, and if sufficient moisture is present, precipitation is formed. Such storms affect a relatively small area and at times cause heavy downpours; however, when the conditions of high temperature and moisture are present, the result is generally one of numerous cells of precipitation. The multiplicity of such convection cells and their movement with the larger patterns of circulation tend to cause precipitation over relatively large areas, although the amount at points within the area may be highly variable.

Orographic precipitation occurs wherever mountain ranges, highlands, or ridges rise above the surrounding country in the path of the moisture-bearing airmasses. An example of this is found on the southwesterly slope of the Appalachian Mountains to which the moisture-laden air is brought by tropical maritime airmasses from the ocean. As a result of the way warm moist air moves from the Atlantic Ocean with the terrestrial air movements and due to the relatively small change in altitude of the terrain, the orographic precipitation is not an important factor in producing storm runoff in the rivers draining the Atlantic coast area States.

It is evident that most of the above types of storms would vary considerably with the months and seasons of the year by the general northward and southward migrations of the planetary wind systems and by variations in convectional activity. Although the annual distribution of precipitation, by months, is rather uniform in the Eastern United States, the winter precipitation is mainly of cyclonic origin resulting from the interaction of moist tropical air from the south and dry polar air from the north. In summer, precipitation is mainly of the convectional and frontal thunderstorm variety. The total quantity of precipitation on an annual basis tends to increase in a southerly direction.

The statistics of storm precipitation are summarized by the U.S. Weather Bureau's Technical Paper 40 (1961). The maximum total amount of rainfall to be expected in a given length of time, at a given location, and for a given return period can be determined. The durations of rainfall are for ½, 1, 2, 3, 6, 12, and 24 hours. The return periods are for 1, 2, 5, 10, 25, 50, and 100 years. The publication also gives the seasonal probability of intense 1-, 6-, and 24-hour rainfalls for eight subareas of the United States east of 105°W. Figure 3 shows a chart from this reference for the seasonal variation of the 6-hour storms in the central Atlantic coast area. This illustration shows, for example, that a storm of an intensity likely to occur on an annual basis has a probability of 1 percent of happening in January and 23 percent of happening in August. This and other charts show that storms of greater intensity and return period are also likely to occur in July and August.

INFILTRATION

In addition to precipitation variation, seasonal variation in infiltration capacity is also an important cause of seasonal variation in stormrunoff. The effects

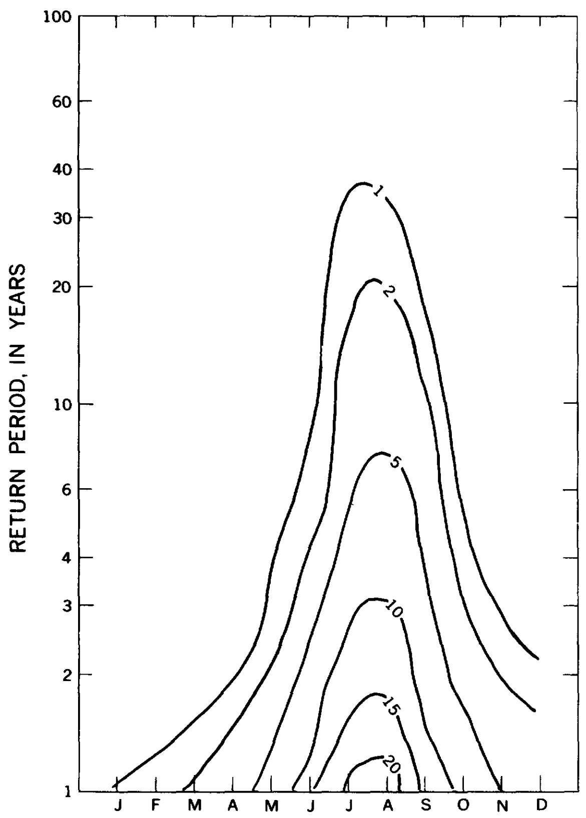


FIGURE 3.—Seasonal probability in percent of an intense 6-hour rainfall for the central Atlantic coast area. (After U.S. Dept. of Commerce, 1961.)

of season and temperature on infiltration were discussed by the author (1951), as follows:

> * * * While resembling the mean temperature curve, the season infiltration capacity curves have a more marked rise in the spring and a more rapid recession in the fall. With respect to actual water temperature, sprinkling from a height of about six feet with water ranging from 40° to 110°F showed no significant differences of infiltration rates. Free, Browning, and Musgrave (1940) found that the contribution of temperature * * * was not a dominant factor in a study of 68 soils. There must then be other factors which largely over-balance the effect of change in viscosity due to change of water temperature. Water at the higher temperatures may cause swelling in the soil which will oppose the effects of decreased viscosity.
>
> —and—
>
> Since changes in water temperature cannot account for seasonal infiltration changes, it is believed that biologic factors are the principal causes. These include soil fungae, earth worms, ants, and beetles. The activity of these biota is largely dependent upon proper moisture conditions which may account for some of the increased variability of infiltration capacity under mid-summer conditions as compared to other seasons of the year.

The rate of storm infiltration would be at a minimum if the soil were frozen. In drainage areas of the central Atlantic area States, soil freezing may occur in varying degrees during part of the year. Topsoil in a wooded area having a good layer of duff and snow cover is protected against freezing at very cold temperatures. The areal extent, depth, and duration of freezing, however, do increase in a northerly direction.

Seasonal variation in infiltration is also a product of several changes in land use during a year. Under agricultural use, the state of cultivation is likely to cause a high infiltration rate under a firmly aggregated soil with a cloddy surface condition and a low rate under a fine-textured soil with an easily dispersed surface condition. The varying condition of the vegetative cover during the season is a critical element in reducing the impact of the raindrop and hence splashing and sealing of the soil pores. Other activities of man and animals tend to compact the soil surface or disrupt vegetative cover in varying amounts during the season.

RUNOFF

The runoff characteristics of a storm depend on the integrated precipitation and infiltration characteristics over a drainage basin and the routing of the resulting precipitation excess to the site on the stream in question. Splash, sheet, and rill erosion, with subsequent transport of fine sediment, is dominant for storms having a great deal of surface or overland runoff. Channel erosion, with subsequent transport of the coarser material found lining the channels, is dominant for storms carrying a great deal of underground runoff. Movement of the coarse material is largely a function of stream hydraulic and roughness characteristics and is therefore more readily correlated with the stage of the stream. This is not so for the fine material since its movement at a stream site is determined largely by erosion of the land surface and the routing with waterflow.

A study of stream sediment movement then should have close correlation with the geographic and seasonal distribution of rainfall erosion potential as determined by Wischmeier (1962). For a specific storm, the most applicable erosion potential was found to be the product of two rainstorm parameters; the kinetic energy of the rainfall in hundreds of foot-tons per acre times the maximum 30-minute intensity in inches per hour. The average of these values for the storms during the year is called the annual erosion index where all factors contributing to soil erosion other than rainfall are held constant. The index is directly proportional to-or closely approximates, the annual soil loss from open cultivated areas. Figure 4 shows a map of the mean annual erosion index for the area of the United States east of 105° W. The approximate seasonal values of the erosion index are shown in figure 5 for central Vermont, central Pennsylvania, central North Carolina, and central Georgia. The increase in magnitude and peakedness of the seasonal indexes from north to south

FIGURE 4.—Mean annual values of Wischmeier's erosion index for the area of the United States east of 105° W.

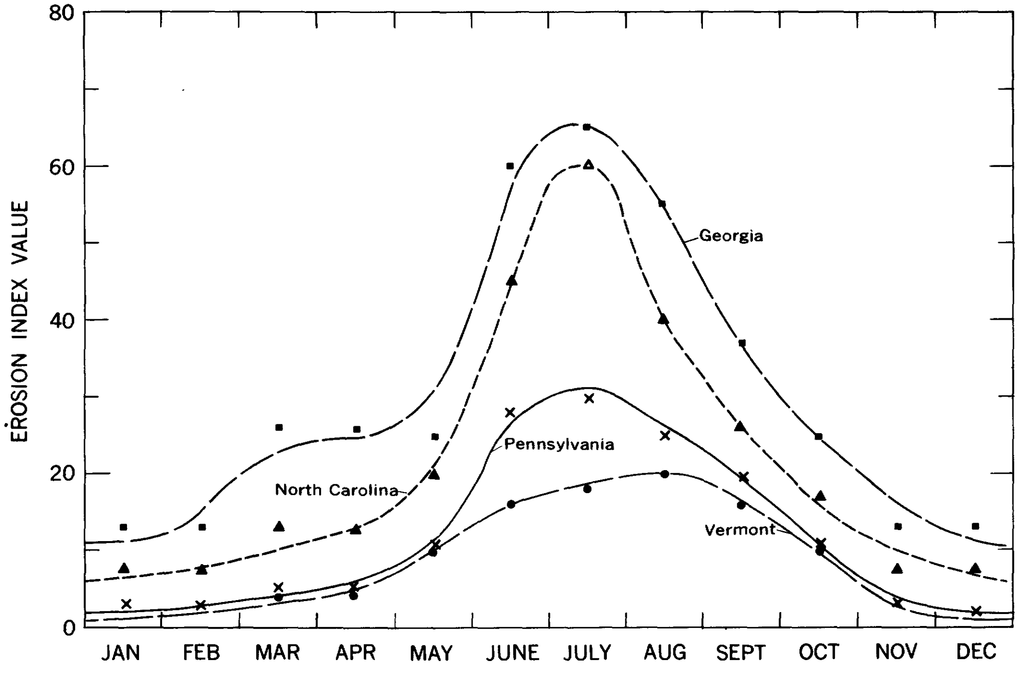


FIGURE 5.—Seasonal distribution of erosion index values at four locations in the Atlantic coast area.

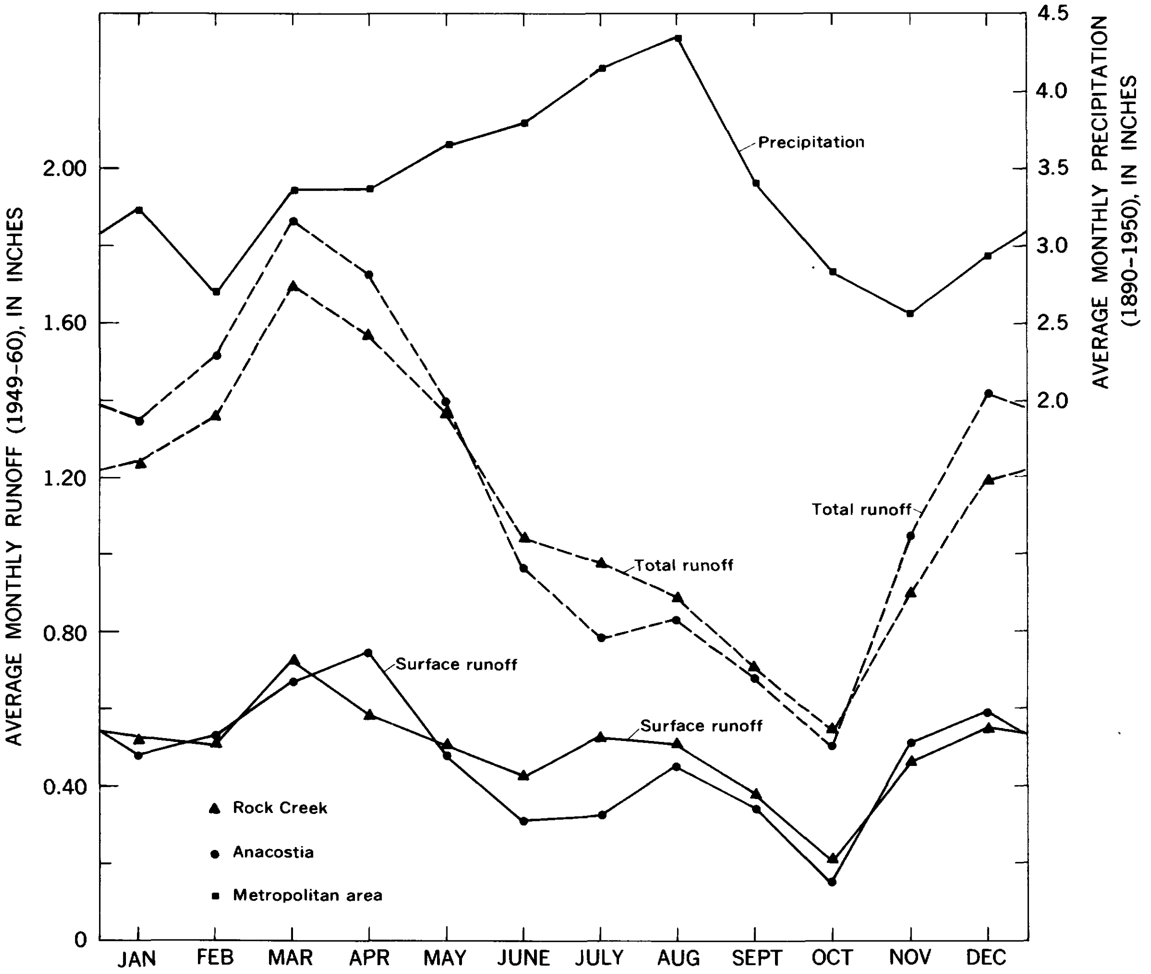


FIGURE 6.—Seasonal distribution of surface and total runoff for Rock Creek at Sherrill Drive, Northwest Branch Anacostia River near Colesville, Md., and precipitation for the Washington Metropolitan area.

in the Atlantic coast area indicates the need for giving greater attention to the passive forces in the south than in the north. The seasonal effect of the erosion index of the important active forces (rainfall parameters) must be integrated with the seasonal effect of the passive forces such as the changes in soil properties and cover if the relative amount of sediment transport in streams is to be evaluated.

Information in the literature on the seasonal variation of surface or overland runoff in streams is lacking. Therefore, the storm-by-storm surface runoff of Rock Creek at Washington, D.C., and the Northwest Branch Anacostia River near Colesville, Md., was computed for the years 1949-60. The land use in these basins, though adjacent to each other, is quite different in that the Anacostia is largely rural in character; whereas Rock Creek is about ⅓ rural, ⅓ urban, and ⅓ in various stages of becoming urban. Figure 6 shows the variation of the monthly average surface runoff as well as the total flow for this 12-year period of flow. The same chart also shows the monthly average precipitation to 1950 for a 60-year period.

As expected, the proportion of surface runoff to total runoff was somewhat greater for Rock Creek than for the Anacostia River due to the greater amount of impervious surface in the Rock Creek basin. The effect of impervious surface is also shown by the fact that Rock Creek has the greatest flow (both surface and total) during the warm season, whereas the Anacostia has the greatest total flow during the cool or low intensity precipitation season. Greater losses by evapotranspiration during the warm season are likely in the Anacostia basin. The seasonal effect of evapotranspiration is very evident when the decreasing total flow of May, June, and July is contrasted with increasing precipitation of these months. The reverse occurs in the fall when the mean flow (both surface and total) increases nearly 100 percent from October to November while precipitation decreases somewhat.

A GRAPHICAL SEARCH FOR VARIABLES

THE STORM EVENT TECHNIQUE

The task of selecting useful correlative, mathematical, and "intuitive" techniques to explain the storm-to-storm variation of sediment moved by a stream is made difficult by the complexity of hydrologic and sedimentologic conditions resulting from the active and passive forces of erosion and from the streamflow characteristics which route the sediment through the channel system. Readily available hydrologic and sedimentologic data, however, will be assembled and tested by correlative techniques. The investigations are limited to the Atlantic coast area and to streams selected from those listed in table 1.

The graphical technique is used to search for suitable variables to explain the nature and cause of sediment discharge variation. Mathematical analysis was avoided at this searching stage because it is more cumbersome to use, and the variance of individual bits of data would be obscured. The graphical technique of multiple correlation using the method of deviations is most adaptable to the "trial and error" and "intuitive" methods for selecting optimum measures for reducing the data scatter and for determining the type of conversions necessary for normalization of the data. In other words, graphical regression is less restrictive than analytical regression in that the model need not be completely specified in advance.

WATER-SEDIMENT DISCHARGE RELATIONS

Of all the data available for streams in the Atlantic coast area, the principle bivariate system for a specific stream location is generally considered to be that of the relation of sediment discharge to water discharge. The sediment-water discharge relation has been used by several investigators to solve specific problems. Campbell and Bauder (1940) used it for comparing discharges in the Red River Basin of Oklahoma and Texas; Miller (1951) for extrapolation of records for the San Juan River of Utah using flow-duration curves, and Leopold and Maddock (1953) for describing the interrelations of measured sediment with other hydraulic variables. One of the most comprehensive reports summarizing the applications of the sediment-water discharge curves is that of Colby (1956).

The sediment-water curves used by these investigators were derived from instantaneous, mean daily, mean monthly, or mean yearly sediment and water discharge data. There are four severe limitations to the curves derived by the instantaneous approach: (1) The sample data may be biased with respect to either time or water discharge because generally measurements are made more frequently at times of high flow and high concentration of sediment, especially during the recession of the runoff hydrograph, than at other times. (2) The sediment concentration of instantaneous samples for a given stream tends to fluctuate about a mean value due to variation in the amount of fine material eroded and transported from upstream tributaries and due to changes in suspension of coarse material at the sampling vertical. (3) The sediment load for small drainage areas is generally, and for large streams is often, much greater for a given water discharge during the rising leg of a storm hydrograph than for the falling leg. (4) Under conditions of relatively high base flow and sediment originating at a considerable distance upstream, it has repeatedly been found that the sediment movement lags behind the flood wave so that the peak sediment concentration may occur after the flood crest.

Figure 7 illustrates the third and fourth concepts. Data from Leopold and Maddock (1953) showed the hysteresis effect for the San Juan River and illustrated that the sediment load for a water discharge of 5,000 cfs (cubic feet per second) is 10 times greater on the rising leg than on the falling leg of the hydrograph. The effect of the progressive lag of sediment movement with respect to the downstream movement of the flood wave is demonstrated by data from Heidel (1956) for the Bighorn River at Manderson and Kane, Wyo.

Water-sediment discharge data plotted from mean daily data, although very convenient because most data are published in this form, have some of the shortcomings exhibited by the instantaneous data; especially the previously mentioned concepts three and four. The small scale variations of concept two are averaged during the 24-hour period, but the 24-hour division of the hydrograph is random, causing undefinable scatter in the relation due to concepts three and four. If the instantaneous or mean daily data were used, the effects of rainfall and possibly other weather and hydrologic conditions would be difficult to evaluate for correlation with sediment discharge due to the complexity of routing their effects downstream to the measuring site.

Monthly and especially yearly plotting cannot be effectively used for lack of sufficient record; at least they would not be effective for making predictions due to the higher standard error of estimate resulting from the small number of points. Each monthly or yearly discharge would be a composite of several hydrologic events, the integrated effect of which would be difficult to ascertain.

On the basis of the above considerations, the storm event is the most logical unit of data to fulfill the objectives of this study. The storm event unit (1) will not bias the curve with untimely data, (2) will average out the instantaneous fluctuations, and (3) will integrate the overall variations of sediment-water conditions over the hydrograph. One important advantage of using

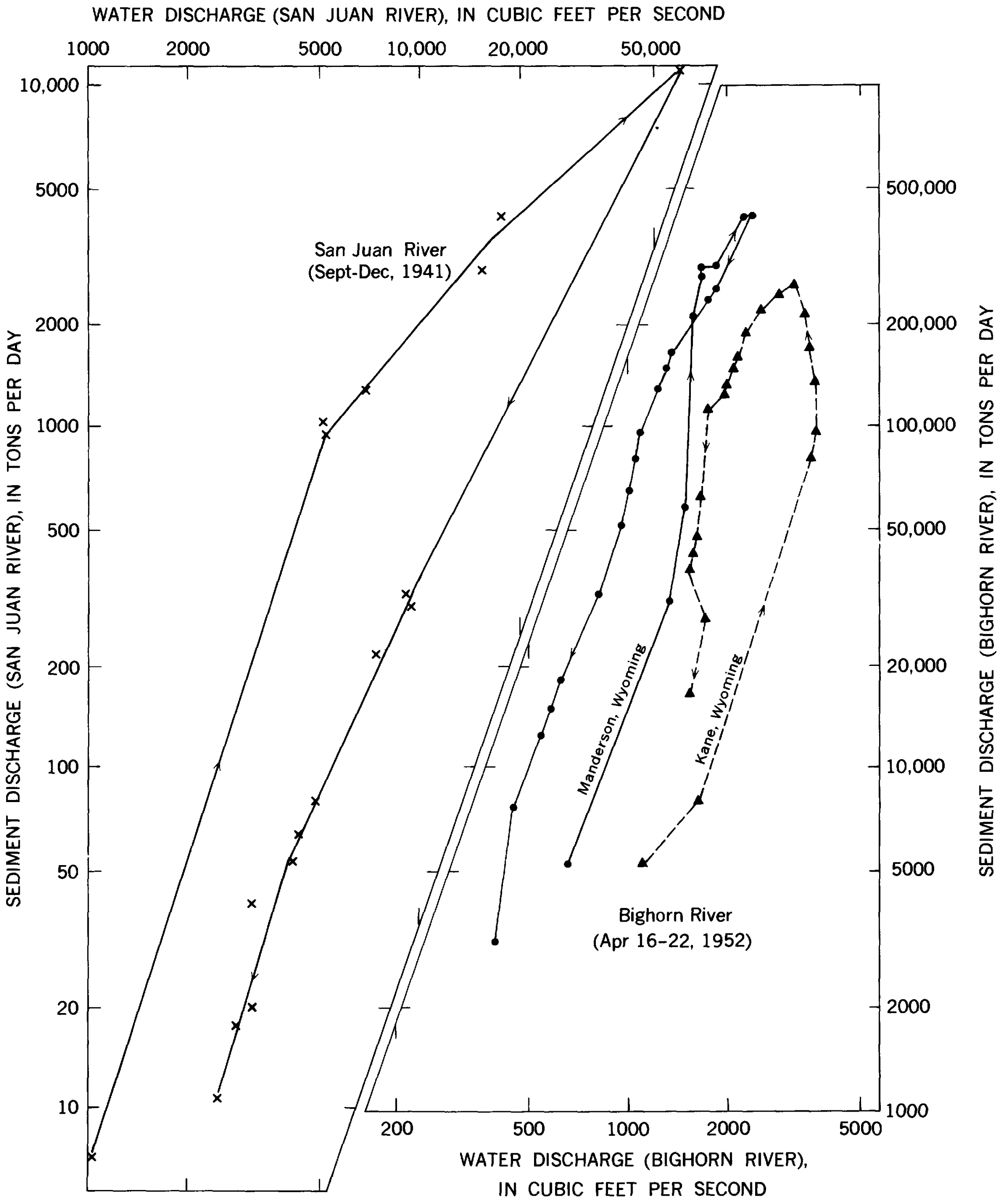


FIGURE 7.—Illustration of variation in water-sediment discharge relations. Effect of hysteresis for the San Juan River. Effect of progressive lag for the Bighorn River.

the storm event unit, especially when only surface runoff is used, is that adjacent storm events are less likely to be related serially than are adjacent instantaneous or daily sediment data. Another advantage is that certain weather and hydrologic conditions can be evaluated for correlation with the sediment-water discharge relation. The two principal disadvantages of the storm event technique are that (1) data are published on the instantaneous, daily, or monthly basis and (2) the sequence of weather may be such that the discharge from different storms may overlap each other in some instances. In the Atlantic coast area, a 3- or 4-year record will generally yield a sufficient number of storm events to adequately define the necessary correlations; whereas, if daily or instantaneous values were used only a sampling of the total data would probably be used to avoid an unwieldy volume of data.

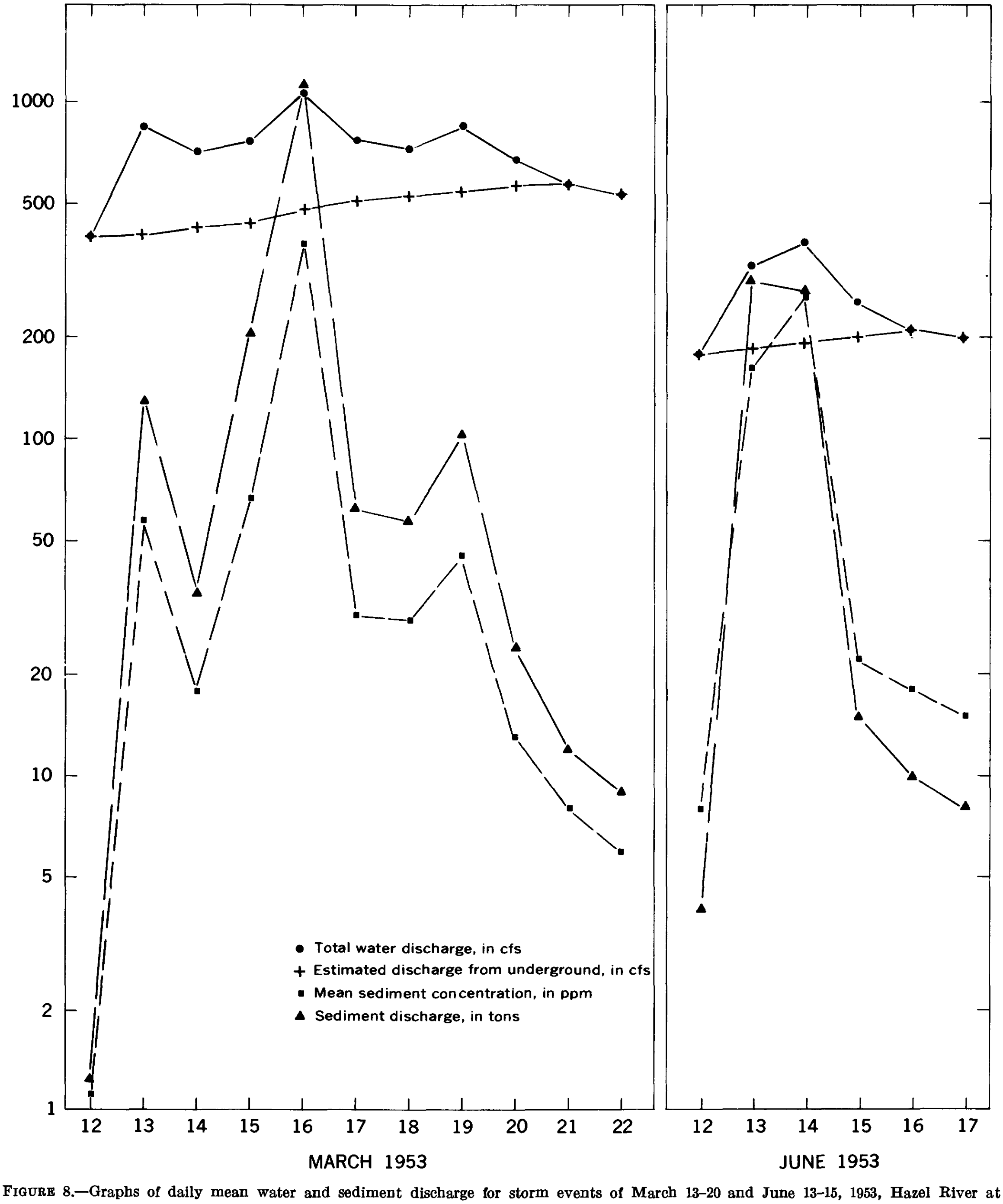


FIGURE 8.—Graphs of daily mean water and sediment discharge for storm events of March 13–20 and June 13–15, 1953, Hazel River at Rixeyville, Va.

COMPILATION OF DATA

Any statistical evaluation of the variation of sediment concentration in streamflow should be conducted so that the principal cause of the variation will be considered first. A reasonably convenient measure of the important storm volume variable is that of the surface runoff past a stream site for a specific storm. Records from the Hazel River at Rixeyville, Va., will be used to illustrate how data are extracted for the storm event technique. Table 2 shows the results for the two storms, March 13–20 and June 13–15, 1953. Graphs of the daily mean total water and estimated underground runoff, or the combined subsurface and groundwater runoff, are plotted with daily mean sediment concentration and daily sediment discharge in figure 8. Computations for the surface runoff and sediment discharge for other storm events were made directly on the tables of published data to eliminate the need for copying the data to tables or plotting hydrographs. Estimated daily values of underground runoff were used that would result in a rounded figure of the net surface runoff for each day, see table 2. Also, as shown in table 2, the sediment discharge for the storm event is the rounded total of all days having net surface waterflow. Mention should be made of the fact that the standard procedures used to obtain the published data omit from consideration the sediment moving near the streambed.

TABLE 2.—*Computation of storm surface runoff and sediment discharge*

[Illustration from record of Hazel River at Rixeyville, Va.]

Date	Total runoff (cfs)	Estimated underground runoff (cfs)	Net surface runoff (cfs)		Sediment discharge (tons)	
1953						
March 12	397	397	0		1	
13	845	405	440	2, 500	130	1, 790
14	712	422	290		35	
15	769	439	330		207	
16	1, 060	480	580		1, 170	
17	769	509	260		62	
18	731	531	200		57	
19	845	555	290		103	
20	676	566	110		24	
21	578	578	0		12	
June 12	178	178	0		4	
13	326	186	140	380	296	580
14	382	192	190		273	
15	252	202	50		15	
16	210	210	0		10	

The water, sediment, and related factors for 75 storm events for the Hazel River from October 1951 to September 1955 are listed in table 3. The basic data for each storm event are described by column numbers as follows:

1. The consecutive number of months during the period of record M_t, beginning with May 1951.
2. The net surface runoff Q_w in cfs-days.
3. The sediment discharge Q_s in tons.
4. The water-discharge-weighted storm event concentration of sediment, $C=\frac{370.4Q_s}{Q_w}$ in ppm (parts per million).
5. The ground-water runoff at the beginning of the storm event, Q_b in cfs.
6. The long-term mean air temperature for the given time of year, T_a in °F.
7. The peak rate of water discharge, less the base flow, P_n in cfs.
8. A peakedness index indicating a measure of storm intensity, $P_i=\frac{P_n}{Q_w}$.
9. The aerial mean precipitation for the basin, R_q in inches, as computed by the Thiessen method.
10. The aerial mean precipitation intensity for the basin, R_i in inches per hour, as computed by the Thiessen method using the hourly data given from recording gages in or near the basin and using only the periods of rainfall for which 0.05 inch or more in a given hour was recorded.

SURFACE RUNOFF

In the search for an explanation of the variation of sediment discharge, the water and sediment discharge data for the Hazel River at Rixeyville, Va. (table 3, columns 2 and 3), were used to plot a sediment transport relation. The data were plotted (fig. 9) with separate symbols for the cool and warm seasons to determine if there is a difference in transport with change of season. The transport curve, which appears to be a straight line on a log–log graph, was drawn approximately through the means of groups of storm events subdivided on the basis of several approximately equal logarithmic intervals of the volumes of water discharge. The division of the data into the two seasons shows three things: first, that the warm season storms have a greater range of water discharge volume; second, that the number of warm season storms greatly exceeds the number of the cool season storms on the side of the higher sediment discharge, and vice versa; and third, at small volumes of water discharge the division is very pronounced, but at large volumes of water discharge the storms for each season are dispersed on both sides of the line.

To visualize how the sediment concentration varies among the storm events, lines of equal concentration for 100, 200, 500, and 1,000 ppm were drawn on the graph. At a small volume of water discharge, for example 500 cfs-days, the concentration lines show that the data scatters from 100 ppm to nearly 1,000 ppm; but, at a large volume of water discharge, for example 10,000 cfs-days, the scatter is less and ranges from about 300 ppm to about 800 ppm.

SEASON

The previously mentioned implications regarding the variation of sediment discharge with season require further testing. The ratio of the observed sediment discharge to that indicated by the transport curve is shown in column 11 of table 3 for each storm. These ratios, when considered as a group, are a measure of the departures or deviations of sediment discharge about the transport curve independent of water discharge or storm size. A plotting of these ratios against their respective time of year (fig. 10) results in a mean curve that varies with time of year, ranging from about 0.50 in February and March to about 1.75 in June and July. The plot also shows again the great diversity in sediment yield of the storms larger than 3,000 cfs-days and their occurrence with all seasons.

TABLE 3.—*Water, sediment, and related factors for storm events of the Hazel River at Rixeyville, Va.*

Date of collection	Time in months M_t (1)	Surface runoff Q_w (2)	Sediment discharge Q_s (3)	Sediment concentration C (4)	Base flow Q_b (5)	Mean air temp. T_a (6)	Peak water discharge P_n (7)	Peakedness index P_i (8)	Mean rainfall quantity R_q (9)	Mean rainfall intensity R_i (10)	Ratio to transport curve (11)
1951											
Nov. 7–10	7	810	510	233	75	48	520	0.64	1.84	0.212	0.66
Dec. 5–9	8	2,230	2,820	469	75	39	2,000	.90	1.94	.270	1.08
Dec. 21–25	8	2,420	1,810	277	190	36	1,250	.52	1.10	.138	.67
1952											
Jan. 5–8	9	960	160	62	270	35	380	.40	.67	.089	.17
Jan. 10–12	9	750	300	148	320	35	520	.69	.82	.091	.43
Jan. 22–24	9	600	170	105	235	35	530	.88	.75	.131	.32
Jan. 27–31	9	1,010	360	132	380	35	700	.69	.85	.075	.36
Feb. 3–9	10	5,250	7,270	512	425	36	3,500	.67	1.79	.152	1.09
Feb. 17–19	10	730	220	111	325	37	520	.71	.99	.099	.33
Mar. 11–17	11	7,630	14,500	704	300	44	4,400	.59	1.66	.133	1.42
Mar. 19–22	11	1,920	1,640	316	490	46	950	.49	.94	.088	.67
Mar. 23–29	11	800	270	125	580	47	300	.38	.86	.084	.36
Apr. 5–9	12	1,100	360	121	465	52	450	.41	.57	.102	.33
Apr. 14–18	12	1,640	1,470	332	430	55	600	.37	1.80	.106	.85
Apr. 24–May 4	12	11,060	6,520	218	430	59	3,500	.31	4.19	.077	.41
May 11–15	13	950	450	175	440	64	600	.63	1.48	.137	.49
May 25–27	13	370	180	180	330	68	250	.68	.90	.166	.57
May 30–June 2	13	430	140	120	325	69	270	.63	.99	.139	.38
June 15–16	14	140	180	476	150	73	160	1.14	.29	.050	1.79
June 22–26	14	1,090	2,330	792	115	74	700	.64	1.44	.193	2.16
June 27–July 2	14	470	860	677	140	75	190	.40	2.44	.432	2.10
July 8–11	15	1,470	1,620	408	110	76	610	.42	2.58	.171	1.07
July 17–18	15	250	360	533	110	76	280	1.12	.26	.143	1.80
Aug. 2–3	16	410	630	569	60	76	450	1.10	1.97	.723	1.80
Aug. 6–11	16	2,700	2,700	370	90	75	2,100	.78	3.08	.226	.89
Aug. 16–17	16	90	60	246	135	72	110	1.22	.77	.430	1.00
Sept. 1–5	17	2,360	4,430	694	90	69	1,900	.80	4.39	.259	1.70
Nov. 15–17	19	300	40	49	80	45	220	.73	.83	.152	.17
Nov. 20–27	19	14,650	20,880	528	115	43	6,200	.42	5.77	.168	.97
Dec. 11–14	20	1,430	1,560	403	330	37	1,000	.70	1.20	.157	1.05
1953											
Jan. 1–4	21	570	130	84	300	35	300	.53	.37	.100	.25
Jan. 8–16	21	4,090	3,470	314	360	35	1,400	.34	1.78	.081	.70
Jan. 24–28	21	2,110	1,880	329	440	35	1,100	.52	1.04	.119	.82
Feb. 15–17	22	670	83	46	270	37	430	.64	.60	.078	.13
Feb. 21–24	22	930	450	179	375	38	500	.54	.45	.103	.50
Mar. 13–20	23	2,500	1,790	265	390	46	800	.32	1.64	.102	.64
Mar. 24–Apr. 1	23	8,720	6,580	279	500	48	2,300	.26	2.77	.189	.55
Apr. 12–17	24	1,870	1,350	267	400	55	800	.43	1.20	.103	.68
May 4–10	25	800	700	324	380	62	300	.38	1.40	.251	.91
May 14–19	25	3,720	7,540	853	310	65	2,200	.59	1.96	.251	1.67
May 20–24	25	1,310	650	183	370	66	750	.57	.82	.113	.49
May 31–June 2	25	510	520	377	280	69	350	.69	.96	.133	1.16
June 13–15	26	380	580	565	175	73	240	.63	.70	.176	1.81
June 22–23	26	360	840	863	150	74	370	1.03	.44	.100	2.80
Aug. 17–19	28	510	510	370	30	73	510	1.00	2.00	.253	1.13
Oct. 28–31	30	290	133	81	30	52	180	.62	2.29	.167	.57
Nov. 23–25	31	290	77	98	45	42	180	.62	1.34	.231	.32
Dec. 7–9	32	490	280	211	105	38	370	.76	1.50	.151	.65
Dec. 13–16	32	1,080	1,200	333	100	37	700	.65	1.38	.104	.84
1954											
Feb. 21–24	34	580	155	99	100	38	490	.84	.80	.132	.30
Mar. 1–8	35	5,240	9,250	652	150	42	2,000	.38	2.88	.256	1.27
Apr. 16–21	36	1,750	450	95	160	56	720	.41	1.83	.113	.24
Apr. 24–30	36	1,750	4,090	866	260	58	600	.34	1.59	.137	1.93
May 3–6	37	700	1,630	861	240	61	400	.57	.98	.104	2.09
May 28–31	37	980	2,200	830	165	69	600	.61	.56	.370	2.32
June 10–13	38	470	750	590	105	72	200	.43	.68	.168	1.83
June 14–15	38	380	570	555	120	72	320	.84	.92	.625	1.78
June 16–21	38	680	530	288	130	73	280	.41	.65	.051	.78
Aug. 20–22	40	100	20	74	10	72	120	1.20	1.08	.063	.30
Aug. 30–31	40	190	100	195	14	70	200	1.05	.98	.090	.69
Oct. 15–18	42	3,210	10,400	1,200	6	56	2,900	.90	6.35	.374	2.85
Nov. 19–22	43	1,030	420	151	80	44	670	.65	1.65	.095	.42
Dec. 14–17	44	1,690	1,130	247	110	36	1,100	.65	1.52	.074	.63
1955											
Dec. 29–Jan. 2	44	1,590	1,230	286	150	35	1,100	.69	1.24	.109	.74
Feb. 6–10	46	1,220	550	167	110	36	800	.66	1.06	.074	.45
Mar. 5–13	47	4,480	3,290	264	220	43	1,400	.31	2.34	.144	.60
Mar. 21–28	47	2,530	1,080	158	255	48	990	.39	1.15	.095	.38
May 22–24	49	220	55	93	150	67	200	.91	.78	.128	.32
June 8–10	50	750	300	148	72	71	430	.57	1.33	.144	.43
June 11–15	50	1,110	550	184	145	72	560	.50	.80	.127	.50
June 19–21	50	260	150	214	140	73	160	.62	.66	.120	.73
July 9–12	51	260	140	199	57	76	220	.85	1.00	.223	.68
Aug. 8–9	52	460	920	740	35	75	540	1.17	1.47	.278	2.30
Aug. 12–16	52	5,610	7,900	522	65	74	4,400	.78	4.33	.251	1.10
Aug. 17–25	52	34,460	41,010	441	225	72	28,700	.83	8.07	.248	.71

The model for analytical computation requires that a numerical linear measure of the seasonal factor be obtained. Assignment of arbitrary numbers to months of the year is not adequate. Since seasonal variation is a result of climate, some measure of climatic variation should logically be suitable. A seasonal curve of the mean monthly air temperature has been found to vary closely with the seasonal variation of sediment dis-

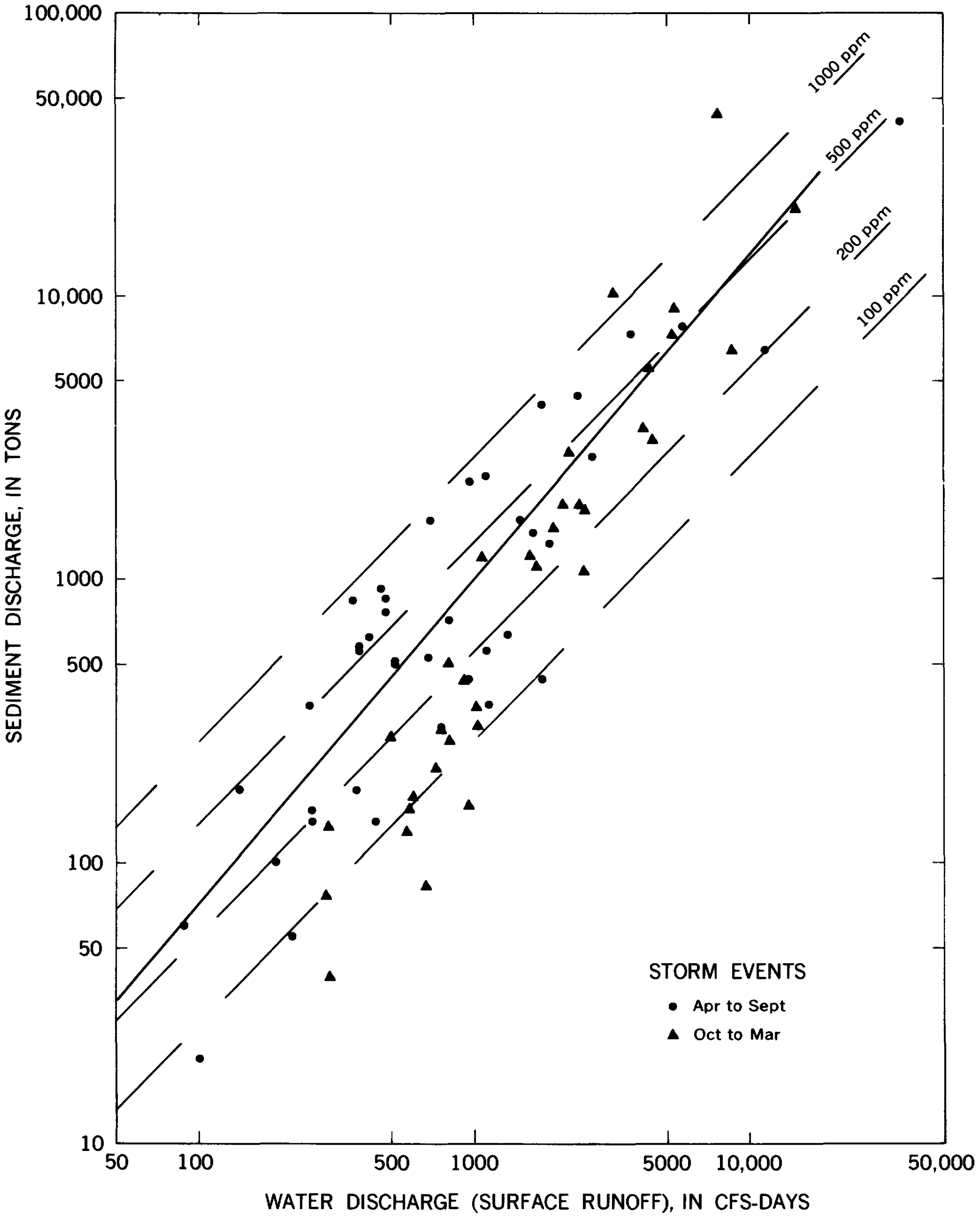


FIGURE 9.—Relation of mean sediment concentration and discharge to water discharge for cold and warm season storm events, Hazel River at Rixeyville, Va.

charge. Figure 11 shows a plotting of the mean air temperature (column 6, table 3) for the date of the specific storms against the same departure ratios or measure of sediment discharge variation. The mean linear regression ranges from a ratio of 0.43 at 35° to 1.45 at 75°. The extremes of the scatter in the plot tend to be parallel to the regression.

GROUND-WATER RUNOFF

Because the amount of runoff and erosion from a drainage basin probably depends on the length of time since the last storm and the condition of the basin with respect to "wetness" and vegetative cover, it is necessary that some measure of the antecedent condition of the basin be used. A reliable determination of the traditional antecedent precipitation index is difficult to obtain for a complete drainage basin. The rate of ground-water runoff of a stream prior to a storm is assumed to be related to the time since the previous storm and the "wetness" of the basin. It has already been noted that the base flow increases during the course of a storm and decreases following the runoff event. Thus, the amount of the ground-water flow at any time will be a function of the length of time and

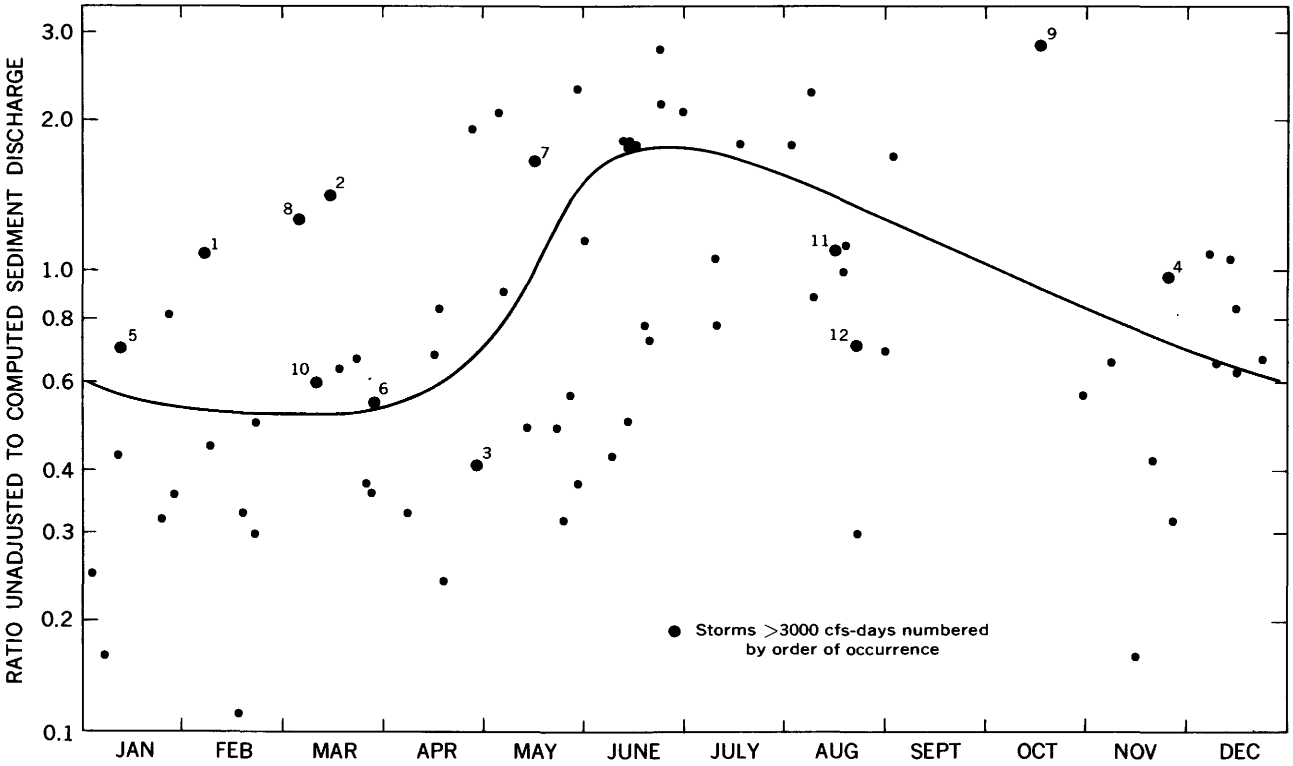


FIGURE 10.—Variation of unadjusted departure ratio or sediment discharge for a given storm size with time of year.

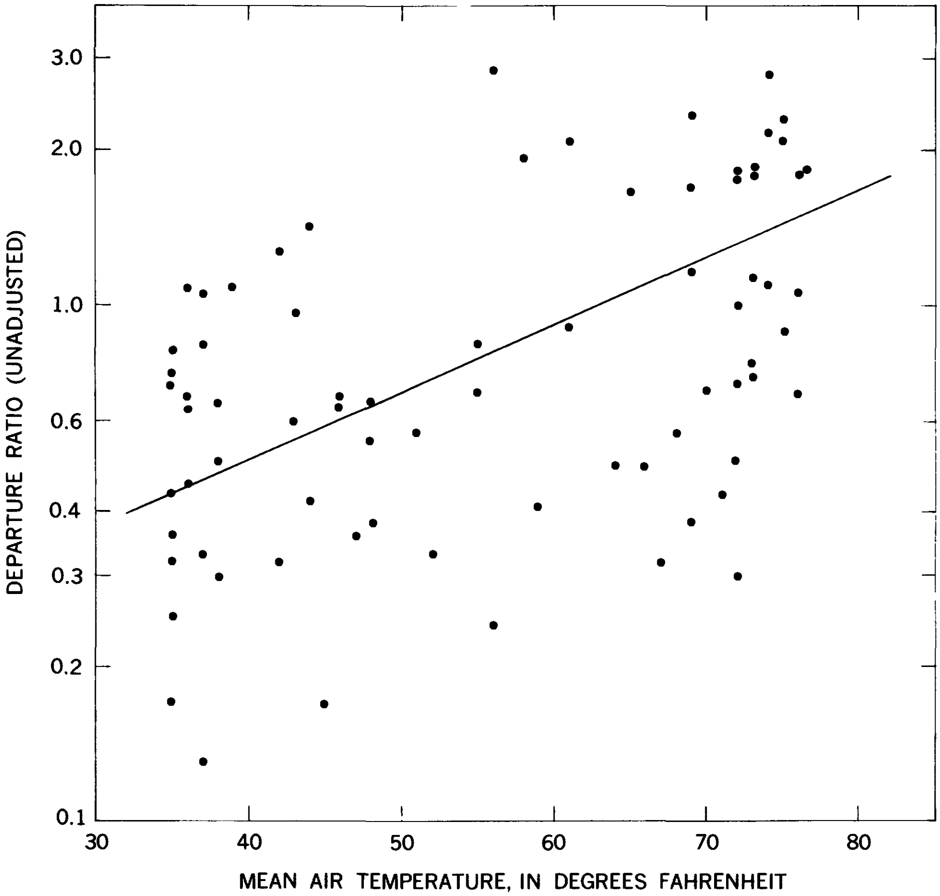


FIGURE 11.—Variation of unadjusted departure ratio or sediment discharge for a given storm size with mean air temperature for time of year of given storm events.

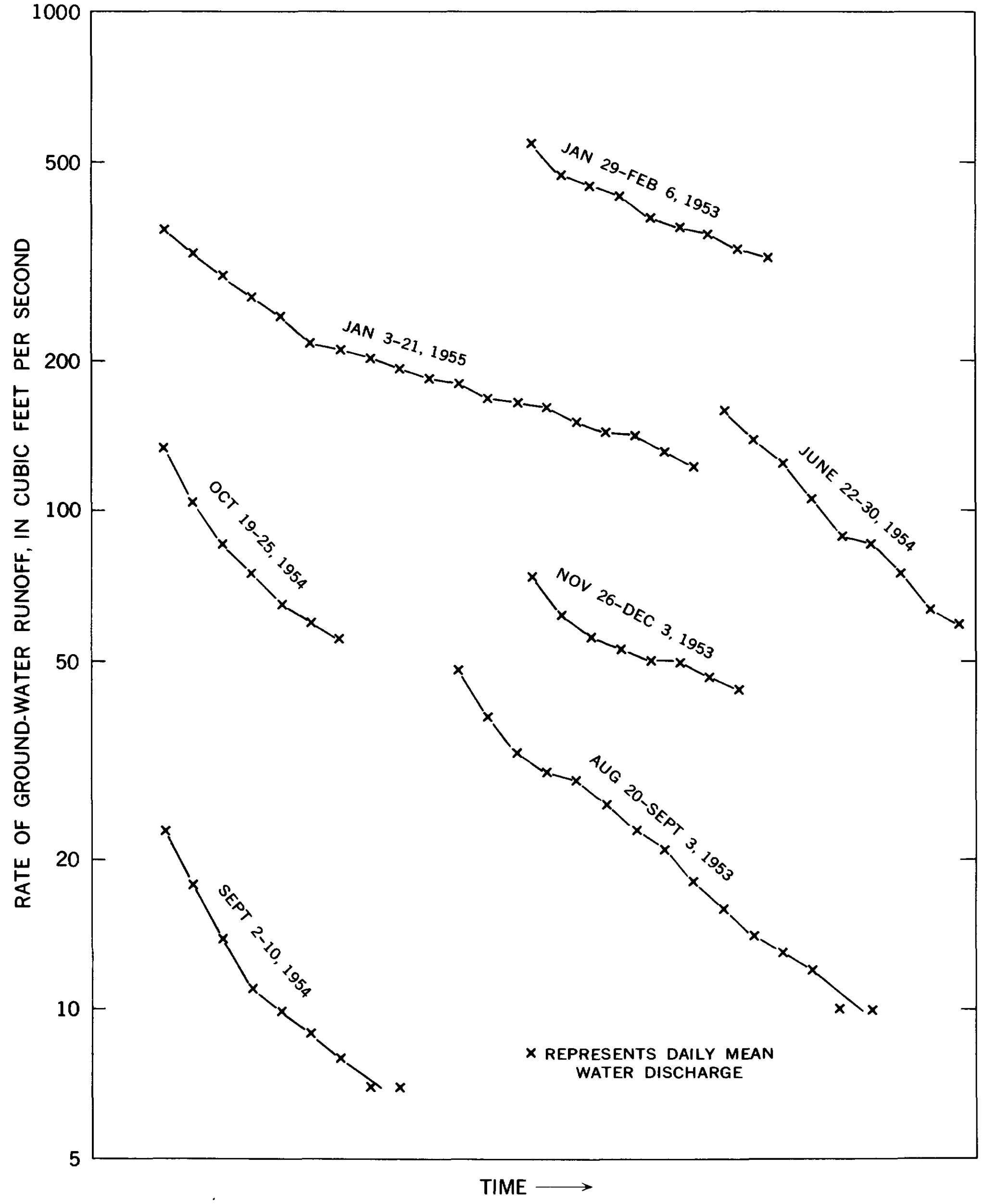


FIGURE 12.—Illustrations of the magnitude and recession of ground-water runoff for Hazel River at Rixeyville, Va.

amount of flow immediately after passage of surface runoff. Figure 12 illustrates several ground-water recession curves for the Hazel River. The recession of flow tends to be steeper and of generally lower magnitude during the warm season than during the cool season, thus again reflecting the seasonal changes of evapotranspiration.

To determine if ground-water runoff, as a measure of antecedent conditions in the basin, is effective in explaining variation in sediment discharge, the departure ratios or measure of sediment discharge variation were plotted (fig. 13) against a logarithmic expression of the base flow (columns 11 and 5, table 3). Again, there are several factors other than ground-water runoff causing a wide variation in the departure ratios, but the trend of the data indicates decreasing sediment concentration with increasing ground-water runoff. As noted from figure 12, the high rate of ground-water runoff generally occurs during the cool season when other factors causing sediment erosion are at a minimum. Further study of ground-water runoff as a variable affecting sediment variation is indicated.

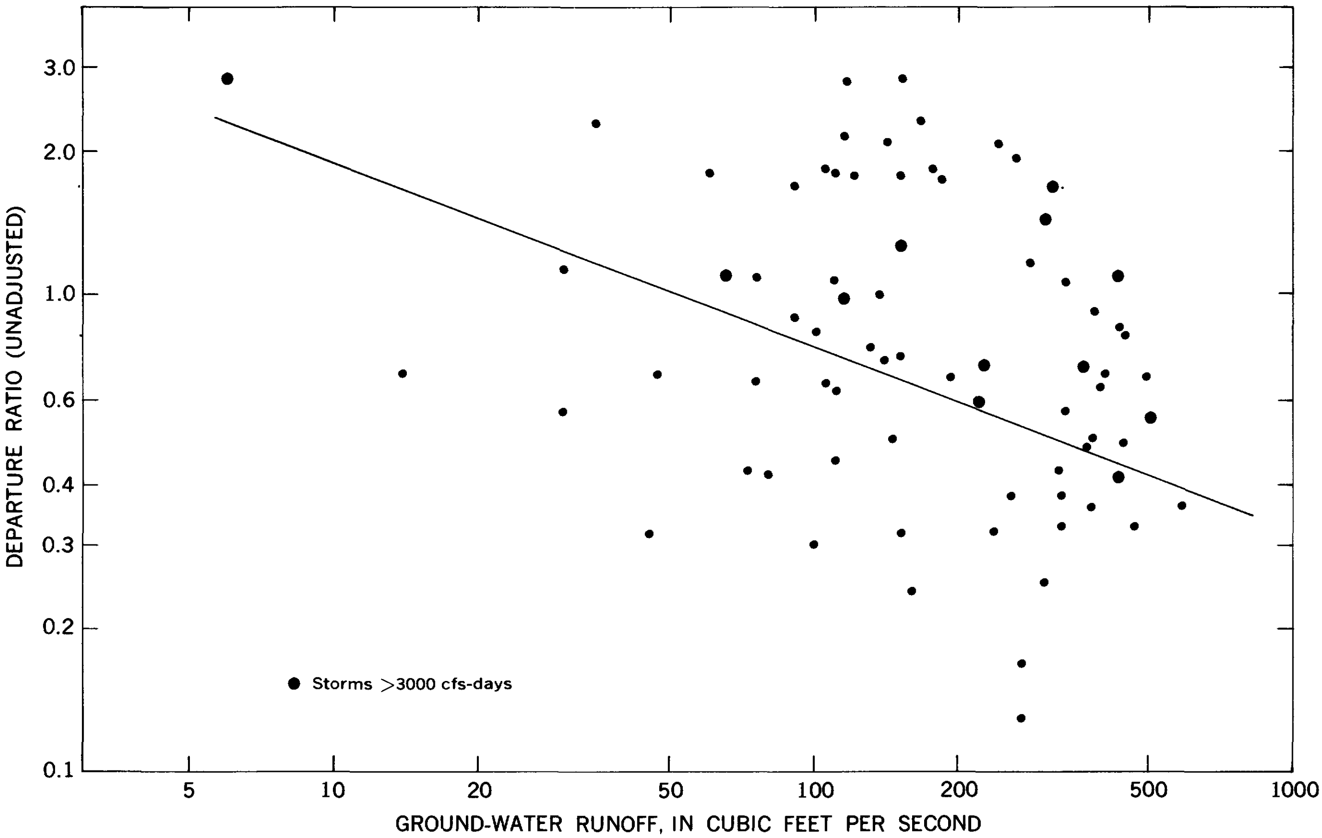


FIGURE 13.—Variation of unadjusted departure ratio or sediment discharge for a given storm size with ground-water runoff.

PEAKEDNESS

Measures of storm intensity should help to explain some of the storm-to-storm variation in the sediment transport relation of figure 9. The intensity of the storm is assumed to affect the rate of erosion and transport. One measure of storm intensity that can readily be obtained from the data at hand, other than rainfall intensity, is the peakedness of the runoff hydrograph. A peakedness index P_i, defined as a ratio of the peak rate of water discharge to the storm runoff volume for the event, is used in these analyses. The underground runoff was also subtracted from the peak flow because this underground runoff varies considerably with season and from storm to storm.

Figure 14 illustrates the relation of the unadjusted departure ratios to the peakedness indexes for the Hazel River data. The plotted data are from columns 11 and 8 of table 3. The general increase of the departure ratio with increase of peakedness index indicates that further study of this factor is desirable.

RAINFALL

Measurement and publication of rainfall data on a daily and hourly basis for a network of stations make it possible to compute by the Thiessen method the storm rainfall quantity and intensity on a particular drainage basin. See page E15 for further definition of the rainfall quantity and intensity factors. The results of such computations may, at times, poorly, represent the actual conditions over the basin due to the variation of the aerial distribution of the precipitation patterns with respect to the small sampling of the event. This is especially true for the thunderstorms that occur during the warm season. The applicability of such data also tends to decrease with decreasing size of drainage area. A small basin of 300 square miles, for example, may not contain a daily gage within its boundaries. There is even a much less chance of such a basin containing a recording rain gage.

In an attempt to use these precipitation data to help explain the variation of sediment discharge for the Hazel River, figures 15 and 16 were plotted to show the relation of the rainfall quantity (R_q) and rainfall intensity (R_i), respectively, to the first departure ratio. The apparent correlation of R_q with the departure ratios is poor, partly due to the error in measuring R_q, partly due to several factors affecting the variation in sediment discharge which cannot be observed, but mostly due to the fact that there is much intercorrelation between R_q and the quantity of runoff already accounted for in deriving the departure ratio. The poor correlation of R_i with the departure ratios is due to the same factors, probably more so in regard to measurement error of R_i and less so in regard to intercorrelation with quantity of runoff. The poor showing of the simple correlation of these precipitation factors with sediment data for the Hazel River does not preclude their application in a system of multiple regression analysis.

TREND

Several of the active and passive factors affecting soil erosion and transport indicated in figure 1 may sufficiently change during the course of a sediment record so that the average storm-to-storm sediment yield may gradually change. Such changes can be detected and evaluated by correlating time or the month M_t from the beginning of the record as an independent variable with the departure ratios. This would then show the variation of the storms and the general trend during the period of record. Data for the Hazel River are shown in figure 17 for both the unadjusted and the seasonally adjusted departure ratios. The unadjusted ratios, plotted on the upper part of the illustration, indicate a somewhat sinuous relation reflecting the seasonal variation as already shown by figures 10 and 11. Such scattering makes the definition of trend of sediment yield more difficult to determine. The bottom part of figure 17 shows a more compact plotting of the sediment variation (nearer to 1.00) owing to the removal of the average seasonal variation. The scatter of the ratios throughout the period of record for the Hazel River for either type of plotting, however, is such that increasing or decreasing trend of sediment yield is not apparent.

CONCENTRATION AS A DEPENDENT VARIABLE

In a multiple regression equation, the regression coefficients are called partial regression coefficients. Each coefficient shows the effect on the dependent variable as a result of a unit change in the particular independent variable, while the other independent variables are held constant.

Sediment discharge, used as the dependent variable in the preceding discussions, is defined as the product of the sediment concentration in the stream, the quantity of water discharge, and a constant. This, then, makes sediment discharge highly interrelated with water discharge, and thus the true independent variable, or sediment concentration, cannot be evaluated in terms of a unit change of water discharge. In other words, sediment discharge will always correlate well with water discharge. For example, a log-log plot of water-sediment discharge data for 10 storms having a wide range of water discharge but each having identical

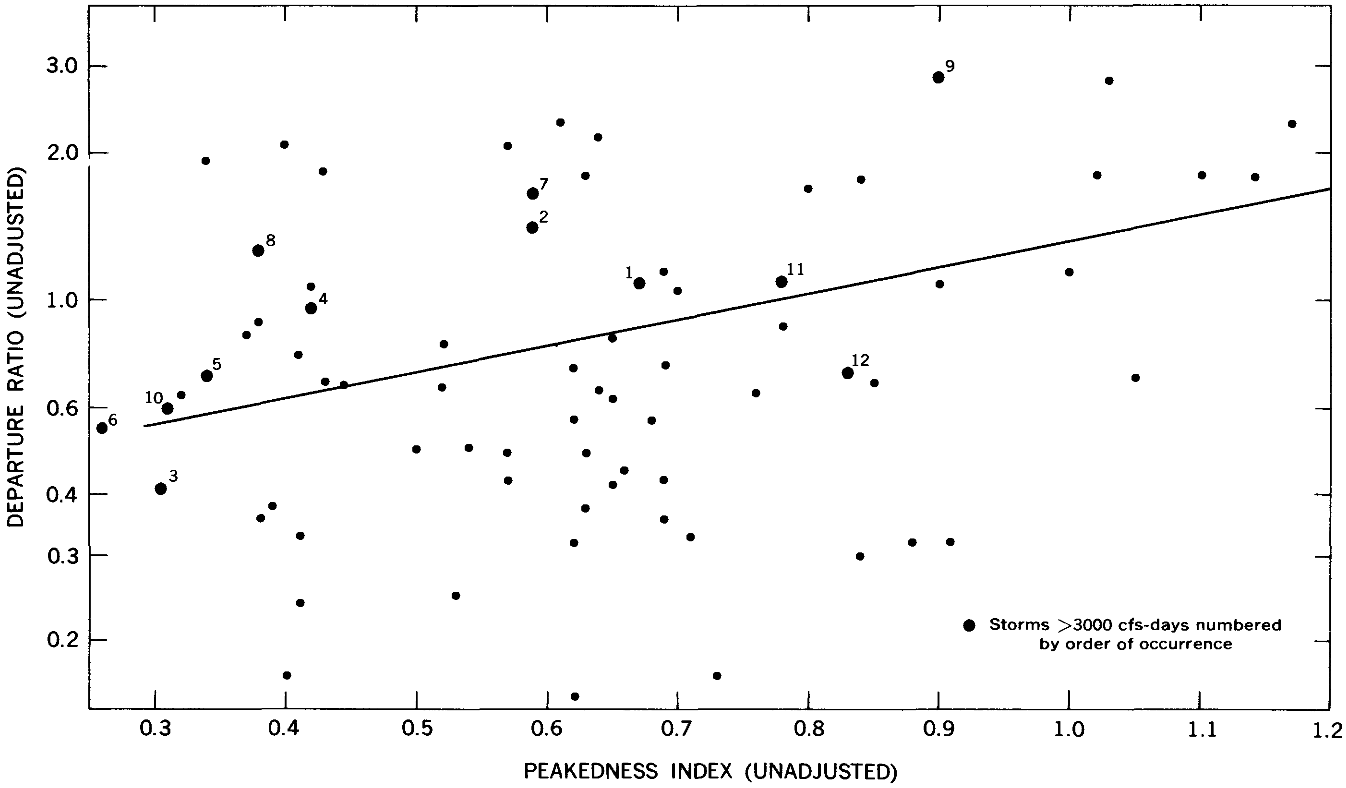


FIGURE 14.—Variation of unadjusted departure ratio or sediment discharge for a given storm size with peakedness index.

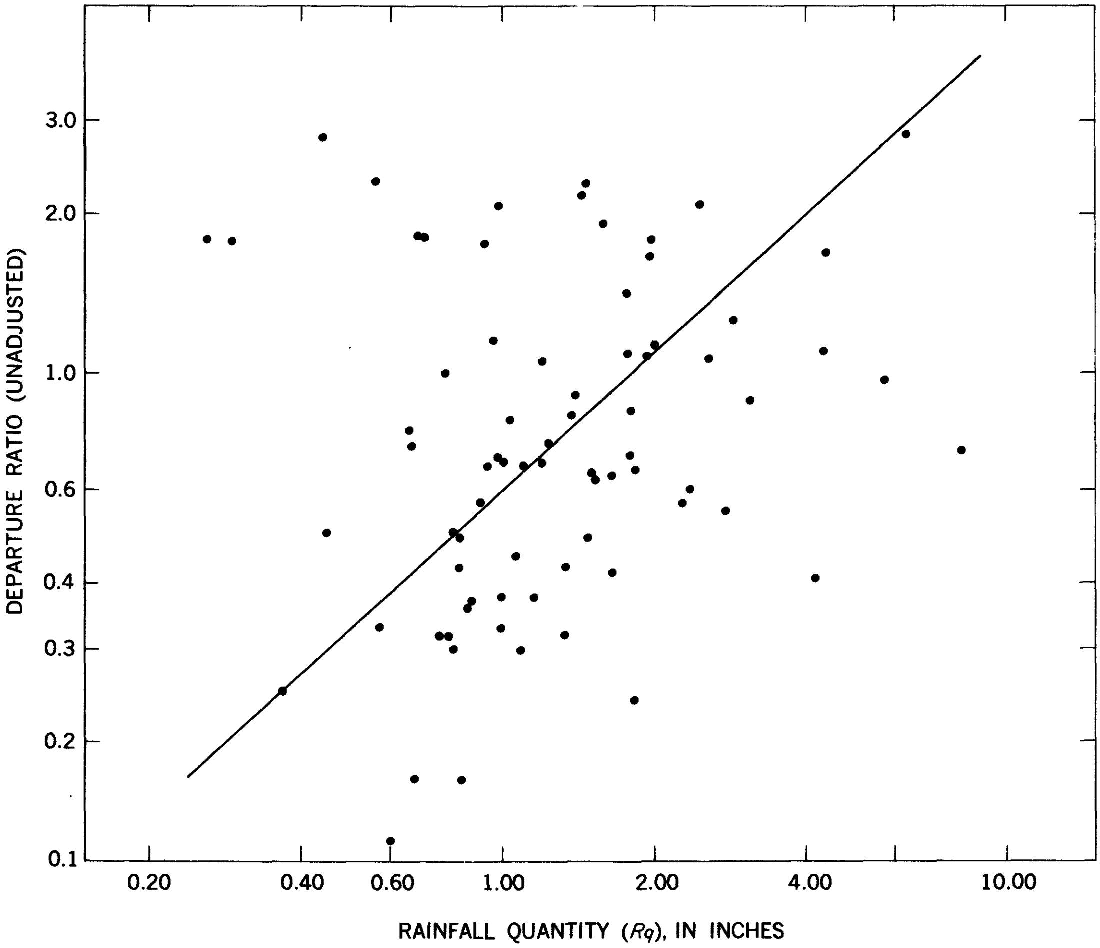


FIGURE 15.—Variation of unadjusted departure ratio or sediment discharge for a given storm size with rainfall quantity.

concentration will result in a perfect and, at first glance, an important correlation with a regression slope of one. On the other hand, if the concentration for these same storms were plotted against water discharge, the correlation and slope of regression would be zero.

Figure 18 shows the relation of mean storm sediment concentration to water discharge for the Hazel River data. The illustration can be compared directly with the sediment-water discharge plotting of figure 9. The apparent correlation between water discharge and concentration is not as good as that between water discharge and sediment discharge. The appraisal of concentration variation (fig. 18) as a dependent variable, however, for a given water discharge is readily visualized, whereas to obtain such an appraisal of concentration from the sediment discharge (fig. 9), it would be necessary to divide the sediment discharge by respective values of water discharge.

The impact of the nature of the storm-to-storm variation is also more apparent when concentration is used. This variation tends to be masked by the intercorrelation effect when sediment discharge is used. For example in figure 18, it is much easier to visualize the need for and to delineate separate curves for the cool and warm seasons than it is in figure 9. It is further readily apparent from figure 18 that the transport curve of figure 9, transposed into concentration terms, was drawn too high at the lower values of water discharge.

SUMMARY OF GRAPHICAL SEARCH

Limitations on time for search of useful variables did not permit the investigation of many conceivable measures or to find the optimum mathematical expression of the variables used. For example, several measures of antecedent conditions may be determined, some based on precipitation quantity and time, some based on ground-water runoff and time, and some based on a measure of moisture deficiency in the basin. Also, measures of the seasonal variation may be tied to climatic factors other than air temperature such as precipitation quantity and intensity in some combination with air temperature, some measure of plant growth and residue, or to Wischmeier's erosion index.

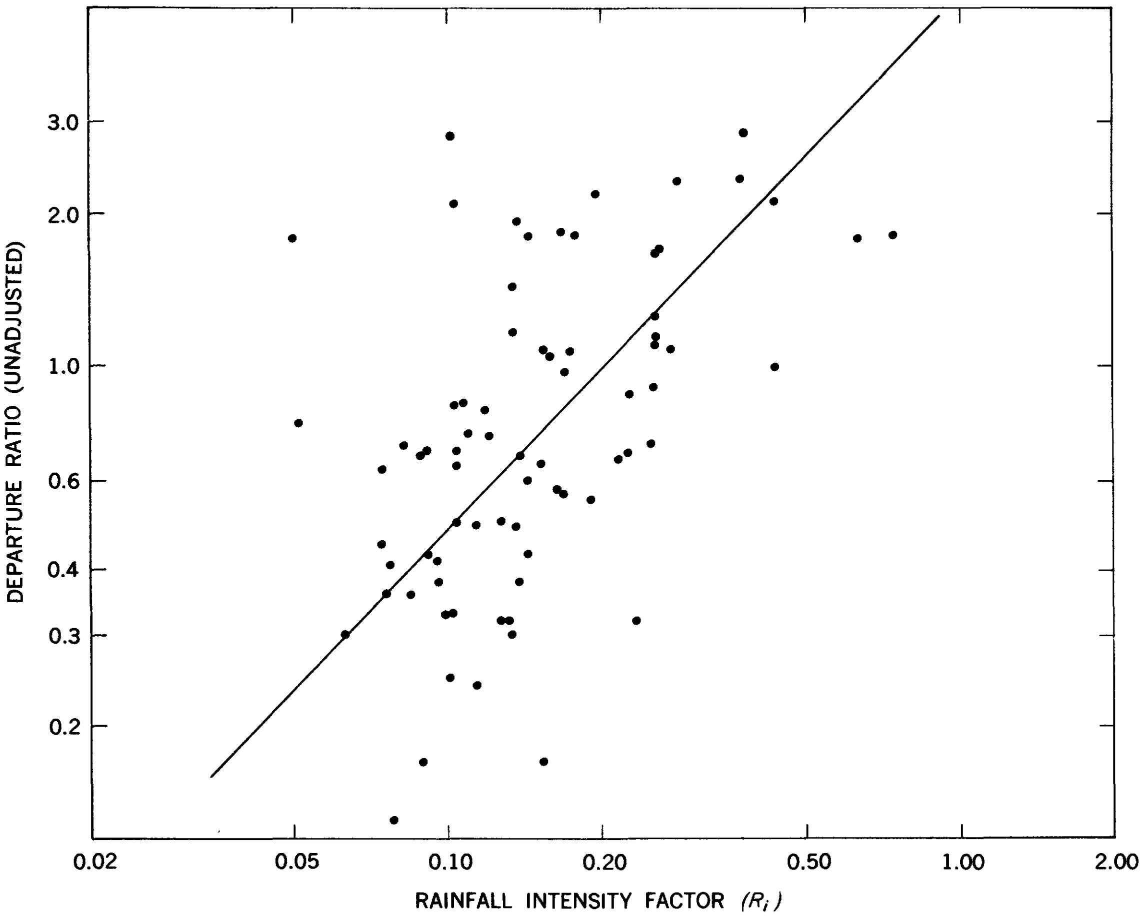


Figure 16.—Variation of unadjusted departure ratio or sediment discharge for a given storm size with rainfall intensity factor.

The graphical phase of the analysis for the sediment records of seven river basins in the Atlantic coast area as listed in table 4, involved plotting or correlating data for each of the 65–138 storm events on 10–25 graphs per basin. Much of this was done before the availability of the computer program and involved trial plots with variables that were noneffective, with other transformations of variables, and with checking on the effect of intercorrelation among the independent variables.

Table 4.—*Sediment records used for correlation and multiple regression analysis*

Stream and location	Drainage area (sq mi)	Period of record used	Number of storm events
1. Scantic River at Broad Brook, Conn.	98.4	Dec. 1952–Sept. 1958	65
2. Brandywine Creek at Wilmington, Del.	314	Dec. 1946–Sept. 1956	138
3. Hazel River at Rixeyville, Va	286	Oct. 1951–Sept. 1956	75
4. Rappahannock River at Remington, Va.	616	May 1951–Sept. 1958	82
5. Rapidan River near Culpepper, Va.	465	May 1951–Sept. 1956	85
6. James River at Buchanan, Va	2,084	do	65
7. James River at Scottsville, Va	4,571	do	67

This graphical search for variables that may be useful in explaining the variation of sediment discharge from storm to storm indicates that:

1. The month during the period of record (M_t) may be used to measure the trend of change with time.
2. The quantity of surface runoff per storm (Q_w) may be used to indicate the magnitude and (or) intensity of erosion and transport. Precipitation quantity (R_q), though difficult to evaluate, may also be used to indicate storm magnitude.
3. The long-term mean air temperature (T_a) for a given time of year can be used as a linear substitute for seasonal changes.
4. The ground-water runoff of the stream immediately prior to storm runoff (Q_b) may be used as a measure of antecedent conditions.
5. The ratio of the peak rate of flow on the storm hydrograph to storm runoff volume (P_t) can be used as a measure of storm intensity which probably affects intensity of erosion and transport. Precipitation intensity (R_i), though difficult to evaluate, may also be used for this purpose.

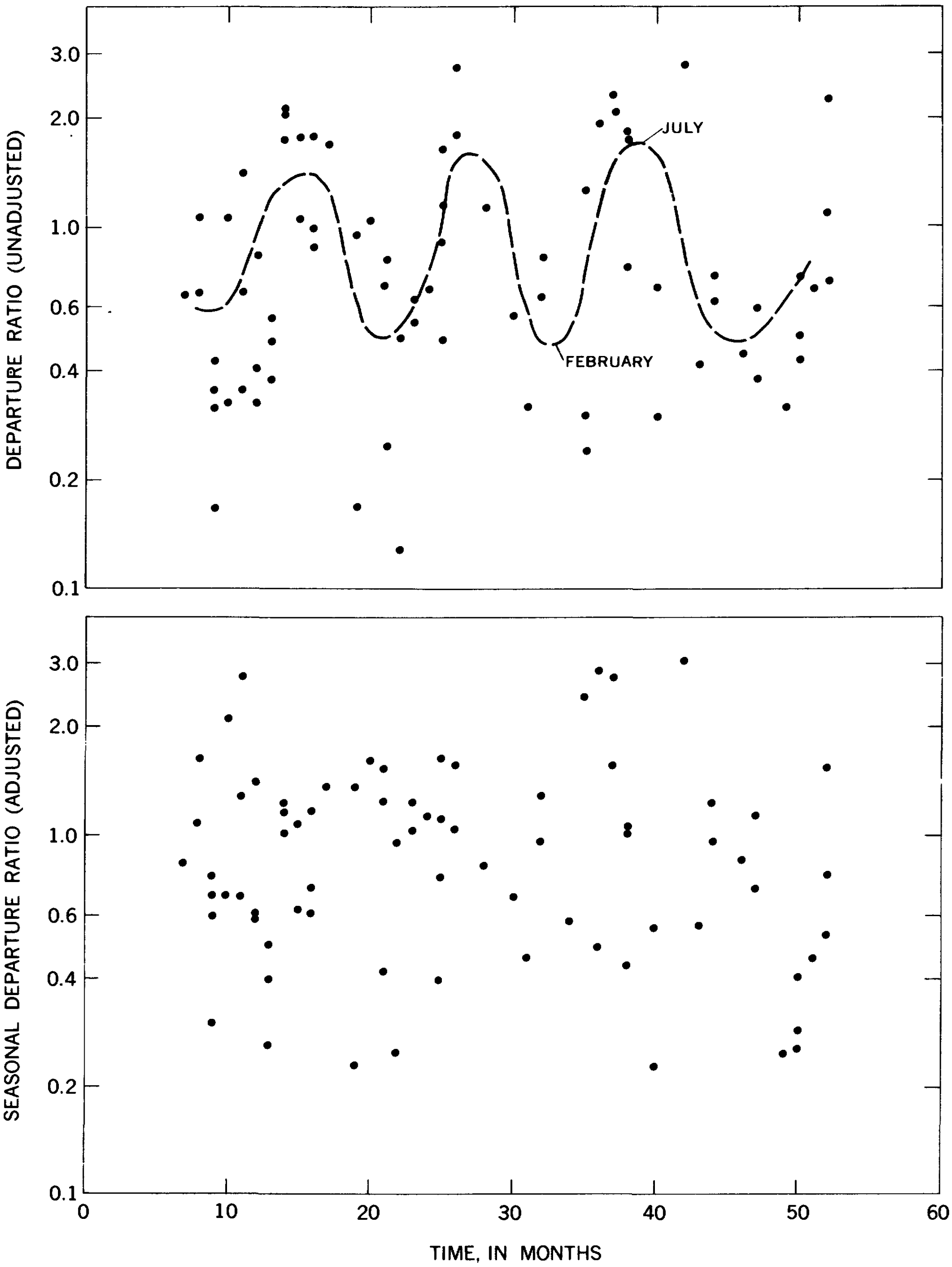


FIGURE 17.—Variation of unadjusted and seasonal adjusted departure ratios with time.

THE MODEL AND TRANSFORMATION OF VARIABLES

Owing to the multiplicity and intercorrelative effects of the variables, it is apparent that the graphical approach to solution or evaluation of the cause of storm-to-storm sediment variation would be difficult and to some degree indeterminate. Also, a rigorous definition of the significance of the regressions found by the graphical approach would not be attainable.

The total effect of all the advantages and disadvantages of the graphical and analytical methods listed by Riggs and others (written communication) is that a combination of the two methods must be used for this problem. Simple graphical correlation must be used to define the appropriate model, to determine the required transformation of the data, and to bring attention to wild points. The analytical method can then be used to obtain the best estimate of the

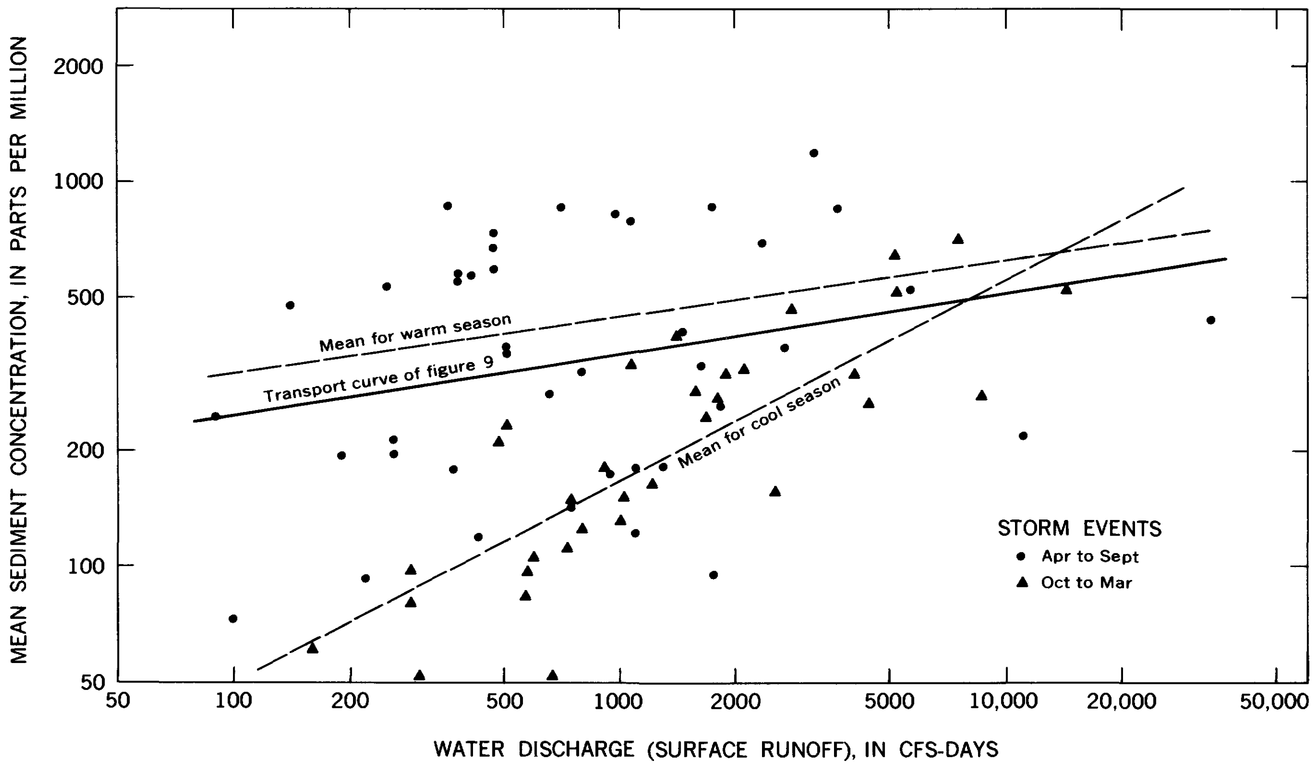


FIGURE 18.—Relation of mean sediment concentration to water discharge for cold and warm season storm events for Hazel River at Rixeyville, Va.

equation coefficients and their significance and the standard error of estimate of the equation. The procedure for making the analytical computations are outlined in most textbooks on statistical methods, such as: Dixon and Massey (1957), Ezekiel and Fox (1959), and Snedecor (1956). The results of the analytical method are unique for the model and sample used and can be presented in a concise manner. Before completion of the multiple regression program for the electronic computer, the "hand" analytical procedure was found to be cumbersome and time-consuming even when as few as two or three independent variables were used. With use of the computer, up to 50 variables may be assimilated and multiple regressions computed from many combinations of the available variables.

Based on the generalized form of the regression model,

$$Y=b_o+b_1x_1+b_2x_2+\ .\ .\ .\ +b_nx_n,$$

the most frequently used models of the basic data for the computer program are as follows:

$$\text{Log } Q_s=b_o+b_1\log Q_w+b_2M_t+b_3T_a+b_4\log Q_b+b_5P_i$$
$$\text{Log } C=b_o+b_1\log Q_w+b_2M_t+b_3T_a+b_4\log Q_b+b_5P_i$$
$$\text{Log } C=b_o+b_1\log Q_w+b_2M_t+b_3T_a +b_4\log Q_b+b_5\log R_q+b_6\log R_i$$
$$\text{Log } C=b_o+b_1\log Q_w+b_2M_t+b_3T_a+b_4\log Q_b+b_5\log P_n$$
$$\text{Log } C=b_o+b_1M_t+b_2T_a+b_3\log Q_b+b_4\log R_q+b_5\log R_i$$

Where Y is the dependent variable, $x_1\ .\ .\ .\ x_n$ are independent variables, $b_o\ .\ .\ .\ b_n$ are constants, and the other symbols are defined on page E15. These combinations of variables are sufficient to define differences due to use of sediment discharge in place of concentration for the dependent variable, and more important to indicate the magnitude of the effects due to measurable factors for storm size, time trend, seasonal variation, antecedent conditions, and storm intensity.

Multiple regression analysis on the electronic computer is programmed so that all variables may either be converted to logarithms or left in the presented form. The above models show that nearly half are arithmetic and the remainder are logarithmic. Therefore, conversion must be done manually for the variables Q_s, C, Q_w, Q_b, P_n, R_q, and R_i. Data for all variables had to be given for a specific observation or storm event. Therefore, some estimates of missing data were made, and in a few instances, the entire observation was omitted. To simplify the logarithmic expression of R_q and R_i, these data were multiplied by 10 and 100, respectively, before conversion.

COMPUTATION RESULTS

The electronic computer program for multiple regression analysis provided options for print-out of the many statistics normally found by longhand computation. The opportunity to check on the approximate accuracy of the original data, some of the internal computations made by the computer, and the statistics summarizing the results and their significance is provided in the print-out of the following:

1. The original data.
2. The arithmetic mean and standard deviation for all variables.
3. The simple correlation coefficients between all pairs of original variables and the t-test for significance.
4. The partial correlation coefficients and test of significance.
5. The multiple regression coefficient and test of significance.
6. The regression weights, their standard error, and test of significance.
7. The regression coefficients, $b_1, \ldots, b_n$.
8. The regression equation constant, b_o.
9. The predicted values of the dependent variable and the residuals between the observed and computed dependent variable.
10. The sums of squares of residuals and standard error of estimate of the dependent variable.

The first three of these items deal with the mass of original data or all variables and observations; whereas, the remaining seven deal with only the variables chosen for a specific multiple regression analysis. Usually, analyses are made of several combinations of the total number of available variables.

The use of a specific variable that is not important or effective in a given multiple regression analysis may increase the standard error of estimate of the dependent variable for an equation. Therefore, one important option on the computer program allows the machine, after completing items 4–10, to automatically reject the variable having the least significant regression weight (item 6) and then to repeat items 4–10 using the new set of variables. This is repeated down to a single independent variable. For example, if seven independent variables were selected for analysis, then the first equation would contain all seven variables, the second equation would contain the six most significant variables of the first equation. The optimum regression equation from a given combination is one with a combination of variables yielding a minimum standard error of estimate.

THE MEANS AND STANDARD DEVIATIONS

The statistics for the mean and standard deviation are listed in table 5 for 10 variables and each of the 7

TABLE 5.—*Means and standard deviations of variables used in multiple regression analysis, by streams*

	Mean concentration (log C)	Sediment discharge (log Q_s)	Water discharge (log Q_w)	Time trend (M_t)	Mean air temp. (T_a)	Groundwater runoff (log Q_b)	Peakedness index (P_i)	Peak flow (log P_n)	Rainfall quantity (log $10R_q$)	Rainfall intensity (log $100R_i$)
Scantic River near Broad Brook, Conn.										
Mean	2.203	----------	2.531	34.02	39.40	2.156	0.852	----------	1.142	1.100
Standard deviation	.154	----------	.385	21.88	13.03	.261	.052	----------	.312	.186
Brandywine Creek at Wilmington, Del.										
Mean	2.519	3.114	3.161	59.75	50.93	2.560	1.383	3.239	1.160	1.234
Standard deviation	.284	.578	.376	32.83	16.53	.232	.511	.382	.226	.310
Hazel River at Rixeyville, Va.										
Mean	2.426	2.887	3.016	26.56	55.63	2.190	0.650	2.807	1.099	1.162
Standard deviation	.335	.672	.501	14.07	15.50	.403	.239	.436	.297	.234
Rappahannock River at Remington, Va.										
Mean	2.543	----------	3.354	28.90	56.79	2.474	0.691	----------	1.120	1.176
Standard deviation	.280	----------	.502	17.76	15.71	.394	.228	----------	.273	.259
Rapidan River near Culpeper, Va.										
Mean	2.540	----------	3.234	28.07	55.40	2.444	0.636	----------	1.159	1.171
Standard deviation	.338	----------	.496	18.05	15.22	.351	.185	----------	.271	.238
James River at Buchanan, Va.										
Mean	2.076	----------	4.144	30.71	53.43	3.171	0.415	3.747	----------	----------
Standard deviation	.323	----------	.505	17.02	13.52	.286	.114	.463	----------	----------
James River near Scottsville, Va.										
Mean	2.367	----------	4.372	28.37	55.36	3.431	0.399	3.959	----------	----------
Standard deviation	.285	----------	.516	18.07	14.63	.309	.118	.472	----------	----------

streams used in the analysis. These statistics are useful for comparing the average characteristics among the streams used in the analysis. For example, the mean air temperature T_a for the time of the storms used is 39.4° for the Scantic River compared with 50.9° for the Brandywine Creek, and 56.8° for the Rappahannock River. The standard deviation measures the central tendency of the data or the degree of scatter; for example, the deviation of log C (concentration) on the Scantic is 0.154 log units, or ± 14 ppm, from the mean of 160 ppm compared to the deviation of 0.335 log units, or ± 22 ppm, from the mean of 266 ppm for the Hazel River.

SIMPLE CORRELATIONS

The independent variables in a regression are generally related to each other as well as to the dependent variable. The interrelation of the independent variables causes the partial coefficients in a multiple regression equation to be different from the simple regression coefficients. In the section, "Summary of graphical search," it was shown that a great deal of this intercorrelation among the variables existed. The simple correlation coefficients among the variables for each of the streams are given in table 6. The significance of each coefficient is indicated where the t-test shows a confidence level of 90 percent or greater.

The data in table 6 shows that several general correlations may be listed:

1. That the mean concentration of sediment for a large number of storm runoff events tends to increase with water discharge, air temperature, peak flow, rainfall quantity, and rainfall intensity.
2. That the sediment discharge tends to increase with water discharge, peak flow, rainfall quantity, and rainfall intensity and decreases with the peakedness index.
3. That the volume of water discharge per storm event tends to increase with ground-water runoff, peak flow, and rainfall quantity and decrease with air temperature and peakedness index.
4. That the ground-water runoff tends to increase with peak flow and decrease with time during the period of record, air temperature, peakedness index, rainfall quantity, and rainfall intensity.
5. That peak flow tends to increase with rainfall quantity.
6. That rainfall quantity tends to increase with rainfall intensity.

Several of these correlations among the variables may not hold for all records as indicated by table 6. A matrix of the variables is shown in table 7 summarizing the data of table 6. The relative values of the coefficients are not shown, but the signs and degree of significance substantiate and further evaluate the above generalizations.

On the two stations where sediment discharge was used in the analysis (Brandywine Creek and Hazel River), the simple correlation coefficients (table 6) are respectively $+0.91$ and $+0.88$ to the effect that sediment discharge will increase with water discharge. Concentration also increases for these stations with water discharge as shown by the highly significant coefficients of $+0.53$ and $+0.32$. The difference in magnitude of the correlation coefficients is due to the fact that the sediment discharge is the product of water discharge, concentration, and a constant. Water discharge correlates well with rainfall quantity, peakedness index, and peak flow; therefore, these elements correlate better with sediment discharge than with concentration due to the intercorrelation between water discharge and sediment discharge.

MULTIPLE REGRESSION EQUATIONS FOR HAZEL RIVER

Data for all 10 variables shown in table 3 were used for the multiple regression analysis for the Hazel River. A detailed comparison between the dependent variables C and Q_s was considered important. For each of these dependent variables, the multiple regression equations for the following combinations of independent variables were determined:

1. Log Q_w, M_t, T_a, log Q_b, P_t, log $10R_q$
2. Log Q_w, M_t, T_a, log Q_b, log $10R_q$, log $100R_t$
3. M_t, T_a, log Q_b, P_t, log $10R_q$
4. Log Q_w, M_t, T_a, log Q_b, P_t
5. Log Q_w, M_t, T_a, log Q_b, log P_n
6. Log Q_w, M_t, T_a, log Q_b, log $100R_t$

By use of the option to repeat the analysis on a given combination after rejection of the least significant variable, these 6 combinations resulted in a total of 32 multiple regression equations for each dependent variable. The 64 equations for the Hazel River from these combinations are shown in the appendix in which each of the above combinations are listed by a separate roman numeral.

Numerals I–VI in the appendix are for the combinations using log C as the dependent variable and VII–XII are for combinations using log Q_s. Evaluation of the relative merits of these dependent variables can be made by comparing the resulting regression coefficients, their significance, and most particularly, the standard error of estimate of the regression equations. Each equation for log C has a lower standard error of estimate than the corresponding equation for log Q_s. The use of log C instead of log Q_s results in a more uniform significance of the regression coefficients.

TABLE 6.—*Simple correlation coefficients and their significance, by streams*

	Mean concentration (log C)	Sediment discharge (log Q_s)	Water discharge (log Q_w)	Time trend (M_t)	Mean air temp. (T_a)	Groundwater runoff (log Q_b)	Peakedness index (P_i)	Peak flow (log P_n)	Rainfall quantity (log $10R_q$)	Rainfall intensity (log $100R_i$)
Mean storm concentration, log C										
Scantic			[1]+0.202	−0.116	+0.130	[2]+0.384	[3]+0.258		−0.038	−0.043
Brandywine		[2]+0.832	[2]+.531	[1]−.142	+.118	−.093	+.000	[2]+0.258	[2]+.456	[2]+.261
Hazel		[2]+.704	[2]+.316	+.058	[2]+.378	−.077	+.078	[2]+.400	[2]+.334	[2]+.470
Rappahannock			[1]+.190	−.052	[2]+.376	−.029	+.065		[3]+.255	[2]+.349
Rapidan			[2]+.380	−.135	[3]+.273	−.020	−.006		[2]+.294	[1]+.204
James, Buchanan			[3]+.309	−.187	+.167	[3]−.274	+.095	[2]+.361		
James, Scottsville			[2]+.647	−.043	−.143	+.190	−.078	[2]+.704		
Sediment discharge, log Q_s										
Brandywine	[2]+0.832		[2]+0.910	−0.075	−0.134	+0.016	[2]−0.367	[2]+0.818	[2]+0.706	+0.045
Hazel	[2]+.704		[2]+.880	+.009	−.056	+.179	[2]−.354	[2]+.881	[2]+.678	[3]+.256
Water discharge, log Q_w										
Scantic	[1]+0.202			−0.176	+0.159	+0.745	−0.115		[2]+0.655	[3]+0.292
Brandywine	[2]+.531	[2]+0.910		−.019	[2]−.228	+.098	[2]−.559	[2]+0.818	[2]+.744	−.121
Hazel	[2]+.316	[2]+.880		−.030	[2]−.318	[2]+.338	[2]−.524	[3]+.949	[2]+.665	+.025
Rappahannock	[1]+.190			+.038	[2]−.294	[2]+.377	[2]−.560		[2]+.660	−.123
Rapidan	[2]+.380			−.113	[3]−.272	[1]+.193	[2]−.548		[2]+.638	−.118
James, Buchanan	[3]+.309			+.040	[2]−.540	[2]+.338	[2]−.468	[2]+.973		
James, Scottsville	[2]+.647			+.065	[2]−.521	[2]+.549	[2]−.506	[2]+.976		
Time trend, M_t										
Scantic	−0.116		−0.176		+0.064	[3]−0.249	−0.131		−0.160	−0.034
Brandywine	[1]−.142	−0.075	−.019		+.044	[1]−.146	+.065	+0.136	−.002	−.082
Hazel	+.053	+.009	−.030		[3]+.256	[2]−.437	+.106	−.011	+.120	+.053
Rappahannock	−.052		+.038		+.161	[2]−.420	−.052		+.180	−.028
Rapidan	−.135		−.113		+.146	[2]−.499	+.117		[1]+.195	−.010
James, Buchanan	−.187		+.040		+.036	[3]−.251	[1]−.215	−.015		
James, Scottsville	−.043		+.065		+.001	−.165	+.141	+.111		
Mean air temperature, T_a										
Scantic	+0.130		+0.159	+0.064		+0.189	+0.097		[2]+0.366	[2]+0.367
Brandywine	+.118	−0.134	[2]−.288	+.445		[2]−.230	[2]+.337	[3]−0.170	+.134	[2]+.597
Hazel	[2]+.378	−.056	[2]−.318	[3]+.256		[2]−.317	[2]+.344	[3]−.238	+.021	[2]+.376
Rappahannock	[2]+.376		[2]−.294	+.161		[2]−.311	[2]+.292		+.130	[2]+.518
Rapidan	[3]+.273		[3]−.272	+.146		[2]−.309	[2]+.330		+.145	[2]+.501
James, Buchanan	+.167		[2]−.540	+.036		[2]−.436	[1]+.239	[2]−.538		
James, Scottsville	−.143		[2]−.521	+.001		[2]−.466	[2]+.426	[2]−.471		
Groundwater runoff at beginning of storm, log Q_b										
Scantic	[2]+0.384		+0.745	[3]−0.249	+0.189		+0.131		−0.108	[3]−0.280
Brandywine	−.093	+0.016	+.098	[1]−.146	[2]−.230		[2]−.263	−0.002	[2]−.256	[2]−.256
Hazel	−.077	+.179	[2]+.338	[2]−.437	[2]−.317		[2]−.576	+.182	[3]−.234	[2]−.308
Rappahannock	−.029		[2]+.377	[2]−.420	[2]−.311		[2]−.536		[3]−.223	[2]−.362
Rapidan	−.020		[1]+.193	[2]−.499	[2]−.309		[2]−.313		[2]−.335	[2]−.412
James, Buchanan	[3]−.274		[2]+.338	[3]−.251	[2]−.436		+.028	[2]+.376		
James, Scottsville	+.190		[2]+.549	−.165	[2]−.466		[2]−.367	[2]+.510		
Peakedness index, P_i										
Scantic	[3]+0.258		−0.115	−0.131	+0.097	+0.131			−0.048	−0.072
Brandywine	+.000	[2]−0.367	[2]−.559	+.065	[2]+.337	[2]−.263		[3]−0.192	[2]−.374	[2]+.339
Hazel	+.078	[2]−.354	[2]−.524	+.106	[2]+.344	[2]−.576		[3]−.259	−.171	[3]+.246
Rappahannock	+.065		[2]−.560	−.052	[2]+.292	[2]−.536			[1]−.197	+.124
Rapidan	−.006		[2]−.548	+.117	[2]+.330	[2]−.313			−.164	+.164
James, Buchanan	+.095		[2]−.468	[1]−.215	+.239	+.028		[3]−.256		
James, Scottsville	−.078		[2]−.506	+.141	[2]+.436	[2]−.367		[2]−.315		
Peakedness, log P_n										
Brandywine	[2]+0.581	[2]+0.818	[2]+0.818	[2]+0.136	−0.170	−0.002	[3]−0.192		[2]+0.609	[3]+0.008
Hazel	[2]+.400	[2]+.881	[2]+.949	−.011	[3]−.238	+.182	[3]−.259		[2]+.714	+.149
James, Buchanan	[2]+.361		[2]+.973	−.015	[2]−.538	[2]+.386	[3]−.256			
James, Scottsville	[2]+.704		[2]+.976	+.111	[2]−.471	[2]+.510	[2]−.315			
Rainfall quantity, log $10R_q$										
Scantic	−0.038		[2]+0.655	−0.160	[2]+0.366	−0.108	−0.048			[2]+0.546
Brandywine	[2]+.456	[2]+0.706	[2]+.744	−.002	+.134	[2]−.256	[2]−.374	[2]+0.609		[1]+.163
Hazel	[2]+.334	[2]+.678	[2]+.665	+.120	+.021	[3]−.234	−.171	[2]+.714		[2]+.404
Rappahannock	[2]+.255		[2]+.660	+.180	+.130	[3]−.223	[1]−.197			[3]+.284
Rapidan	[2]+.294		[2]+.638	[1]+.195	+.145	[2]−.335	−.164			[2]+.292
Rainfall intensity, log $100R_i$										
Scantic	−0.043		[3]+0.292	−0.034	[2]+0.367	[3]−0.280	−0.072		[2]+0.546	
Brandywine	[2]+.261	+0.045	−.121	+.082	[2]+.597	[2]−.265	[2]+.339	+0.008	[1]+.163	
Hazel	[2]+.470	[3]+.256	+.025	+.053	[2]+.376	[2]−.308	[3]+.246	+.149	[2]+.404	
Rappahannock	[2]+.349		−.123	+.028	[2]+.518	[2]−.362	+.124		[3]+.284	
Rapidan	[1]+.204		−.118	−.010	[2]+.501	[2]−.412	+.164		[2]+.292	

[1] Poorly significant (90 percent level).
[2] Highly significant (99 percent level).
[3] Significant (95 percent level).

TABLE 7.—*A matrix of variables showing the average direction and significance of simple correlations*

[+ or − is used when two-thirds or more of records show the respective sign. ± is used when more than one-third of records show both signs]

	Log C	Log Q_s	Log Q_w	M_t	T_a	Log Q_b	P_i	Log P	Log $10R_q$	Log $100R_i$
Log C	------	[1]+	[2]+	−	[3]+	−	+	[1]+	[2]+	[2]+
Log Q_s	[1]+	------	[1]+	±	−	+	[1]−	[1]+	[1]+	[3]+
Log Q_w	[2]+	[1]+	------	±	[1]−	[3]+	[1]−	[1]+	[1]+	±
M_t	−	±	±	------	+	[2]−	±	±	±	±
T_a	[3]+	−	[1]−	+	------	[1]−	[1]+	[1]−	+	[1]+
Log Q_b	−	+	[3]+	[2]−	[1]−	------	[1]−	[3]+	[2]−	[1]−
P_i	+	[1]−	[1]−	±	[1]+	[2]−	------	[2]−	−	+
Log P	[1]+	[1]+	[1]+	±	[1]−	[3]+	[2]−	------	[1]+	+
Log $10R_q$	[2]+	[1]+	[1]+	±	+	[3]−	−	[1]+	------	[2]+
Log $100R_i$	[2]+	[3]+	±	±	[1]+	[1]−	+	+	[2]+	------

[1] Highly significant (99 percent level).
[2] Significant (95 percent level).
[3] Poorly significant (90 percent level). Where no footnote is shown, correlation is not significant

The nonuniformity of significance for log Q_s is caused by the very high degree of simple correlation between log Q_s and log Q_w which results in log Q_w assuming more than its share of significance from the total regression.

In the instance when log $10R_q$ is used instead of log Q_w (compare combinations III and IV with X and XI), the minimum standard error is found to be 0.295 and 0.444, respectively, for log C and log Q_s. In other words, if log Q_s must be used, then it is essential that log Q_w be included as one of the independent variables; whereas, if log C is used, then the more uniform degree of intercorrelation among the independent variables results in a stronger equation. The use of log C instead of log Q_s also tends to increase the significance of P_i, log $10R_q$, and log $100R_i$ and tends to somewhat decrease the significance of log Q_b.

The usefulness of specific independent variables to predict sediment conditions in a stream is based on their statistical significance and numerical value in the equation. When log C is used as the dependent variable, the following observations from the appendix for the Hazel River data seem pertinent.

1. The measure of ground-water flow for antecedent conditions log Q_b is not effective. Only some equations in II and III, for example, rate as high as very poorly significant.
2. The coefficients for M_t or time trend are all negative, indicating the possibility of decreasing sediment during the period of record; however, it is not significant for any equation.
3. Runoff volume or log Q_w is a better measure of storm volume than is rainfall quantity or log $10R_q$ (contrast I–2 with III–1 and the respective S_e of 0.270 and 0.297).
4. Net peak flow log P_n is only a slightly better measure for a storm intensity factor than is peakedness index P_i (contrast IV and V).
5. Due to a large amount of intercorrelation, use of log P_n makes log Q_w insignificant (see V).
6. When only two independent variables are used, log P_n and T_a yield better results than log Q_w and T_a (contrast V–4 and I–5).
7. Log $100R_i$ is the best measure of storm intensity when contrasted with the measures of peakedness P_i and log P_n.

As a result of the characteristic intercorrelation among variables and their expected variation for different drainage basins, the conclusions noted above for the Hazel River cannot be rigorously applied to other streams. On the basis of hydrologic and sedimentologic theory, however, these conclusions are logical and should, within limits, find general application.

COMPARISON OF STREAMS

The two principal objectives of this analysis were to define the effect of specific measurable independent variables on the variation of sediment in streamflow for specific locations and to determine how these effects change from basin to basin. As in the above analysis of the Hazel River, the regression coefficients, their significance, and the standard error of estimate for the equations will be compared to show these effects for seven locations in the Atlantic coast area.

The regression equations and their standard error of estimate and the significance of coefficients for several combinations of variables for the seven locations are given in the appendix. The constants or regression coefficients and their significance for two or more combinations of variables for each of the seven locations are shown in table 8. Equations were chosen for this table which demonstrated a minimum standard error of estimate and yet used the principal combination of available and applicable variables.

EFFECTS OF DEPENDENT VARIABLES

The results of comparing the dependent variable log Q_s (sediment discharge) with the dependent variable log C (concentration) for the Hazel River were not conclusive in some respects. Therefore, a similar comparison was made for the Brandywine Creek. The two most important conclusions determined from the Brandywine data, which are similar to those determined for the Hazel River, are (1) that the standard error of estimate is less for log C than for log Q_s but not appreciably so, and (2) that the very high significance of log Q_w (water discharge) when log Q_s is used causes a tendency for the remaining independent variables to lose significance.

TABLE 8.—*Regression coefficients and standard error of estimate of principal regression equations, by streams*

	Equation constant[1]	Water discharge (log Q_w)	Time trend (M_t)	Mean air temperature (T_a)	Ground-water runoff (log Q_b)	Peakedness index (P_i)	Peak flow (log P_n)	Rainfall quantity (log 10 R_q)	Rainfall intensity (log 100 R_i)	Standard error of estimate (± S_e in log units)
Scantic River at Broad Brook, Conn.										
Surface runoff	+1.551	[2] +0.143			[2] +0.117	[2] +0.037		[3] −0.113		0.138
	+1.492	[2] +.135		+0.00112	[2] +.196			[3] −.149	+0.068	.143
Total runoff	+.031	[4] +.503	−0.00102		[2] −.206	[4] +1.205				.177
	+.034	[4] +.423	+.00120		[3] −.148	[4] +1.159		[3] +.121		.178
	+.241	[4] +.460	[3] +.00157		[2] −.239				[2] +.290	.198
Brandywine at Wilmington, Del.										
Log C	+0.886	[4] +0.644	[5] −0.00155	[2] +0.00385	[2] −0.195			[2] −0.365	[5] +0.338	0.215
	+1.039	[2] +.325	[4] −.00199	[4] +.00554	[2] −.183		[4] +0.333	[6] −.274		.211
	+.406	[4] +.719	[5] −.00150	[4] +.00484	[3] −.124	[4] +0.196		[3] −.232		.208
Log Q_s	−1.634	[4] +1.633	[2] −.00142	[2] +.00365	[2] −.199			[2] −.345	[5] +.328	.216
	−1.494	[4] +1.310	[5] −.00187	[4] +.00526	[2] −.185		[4] +.336	[3] −.262		.212
	−2.095	[4] +1.705	[2] −.00137	[5] +.00462	[3] −.131	[4] +.189		[3] −.225		.210
Hazel River at Rixeyville, Va.										
Log C	+0.642	[4] +0.513	−0.00256	[4] +0.00970	[3] −0.178			[2] −0.421	[4] +0.533	0.255
	+.791	−.098	−.00200	[4] +.01083	−.021		[6] +0.509			.269
	+.586	[4] +.397	−.00242	[4] +.01101	−.040	[3] +0.278				.270
	+.660	[4] +.474	−.00289	[4] +.01153	−.105	[3] +.258			+.149	.270
Log Q_s	−1.644	[4] +1.406	−.00254	[4] +.00837	[3] −.184			−.252	[5] +.493	.265
	−1.401	[4] +1.029	−.00269	[4] +.01005	−.119		+.341			.278
	−1.464	[4] +1.355	−.00308	[4] +.01025	[3] −.144	+.143				.280
	−1.456	[4] +1.363	−.00313	[4] +.01030	−.151	+.141			−.016	.282
Rappahannock River at Remington, Va.										
	+1.328	[2] +0.323	[3] −0.00276	[4] +0.00925	−0.092	+0.154		−0.171		0.247
	+1.395	[5] +.325	[3] −.00278	[4] +.00804	−.117			−.257	[6] +0.221	.245
Rapidan River near Culpeper, Va.										
	+0.768	[4] +0.529	[3] −0.00284	[4] +0.00959	−0.121	[6] +0.395		[3] −0.300		0.280
	+1.141	[4] +.449	−.00268	[4] +.00947	−.126			[3] −.283	+0.113	.287
James River at Buchanan										
	+0.960	[5] +0.532	[5] −0.00530	[5] +0.00777	[4] −0.556	[4] +1.019				0.230
	+1.783	[6] +.486	[5] −.00621	[5] +.00807	[4] −.572		[4] +1.027			.229
James River at Scottsville										
	+0.211	[4] +0.560	[2] −0.00297	[3] +0.00286	[2] −0.196	[5] +0.770				0.194
	+.832	[3] −.359	[2] −.00322	[3] +.00290	[6] −.184		[4] +0.926			.186
Equations of minimum S_e										
Scantic	+1.551	[2] +0.143			[2] +0.177	[2] +0.037		[3] −0.113		0.138
Brandywine	+.406	[4] +.719	[5] −0.00150	[4] +0.00484	[3] −.124	[4] +.196		[3] −.232		.208
Hazel	+.642	[4] +.513	−.00256	[4] +.00970	[3] −.178			[2] −.421	[4] +0.533	.255
Rappahannock	+1.333	[5] +.187	[3] −.00211	[5] +.00711					[6] +.204	.244
Rapidan	+.355	[4] +.524		[4] +.00970		[2] +.429		[6] −.275		.281
James, Buchanan	+.960	[5] +.532	[5] −.00530	[5] +.00777	[4] −.566	[4] +1.019				.203
James, Scottsville	+.211	[4] +.560	[2] −.00297	[3] +.00286	[2] −.196	[5] +.770				.194

[1] The dependent variable is log C except where noted for Brandywine Creek and Hazel River.

[2] Significant (95 percent level).

[3] Very poorly significant (80 percent level).

[4] Very highly significant (99.9 percent level).

[5] Highly significant (99 percent level).

[6] Poorly significant (90 percent level).

EFFECTS OF INDEPENDENT VARIABLES

The effects of selected independent variables on variation of sediment discharge can be determined by study of the coefficients and their relative significance as given in table 8 and the appendix. Again, it is noted that variation of coefficients for a specific variable at a specific stream location is largely due to the effect of intercorrelation among the independent variables. An outstanding example of this is shown by the difference in the first two equations for the Brandywine Creek in table 8. The first equation used rainfall intensity and the second equation uses peak flow as a measure of storm intensity. The first equation has a highly significant coefficient for log Q_w of +0.644, and the second equation has a less significant coefficient for this variable of +0.325. The difference is attributed to a highly significant coefficient of +0.333 for log P_n in the second equation and to the fact that peak flow has a very strong simple correlation with the quantity of water discharge for a storm period.

The significant regression coefficients in table 8 are usually of the same variables that had significant simple correlation with sediment concentration. See the first section of table 6. Generally, the significance of a specific regression coefficient is improved over that of the simple correlation due to the effects of the multiple regression in isolating the effects of a single variable. For example, the simple correlation coefficients of concentration with time trend for the Brandywine Creek is poorly significant (table 6); whereas, the regression coefficients for time trend (table 8) are all highly significant. In other instances the simple correlation coefficients are not significant at the level tested, but the regression coefficients are significant.

The regression coefficients tend to have the same sign as the simple correlation coefficients, especially so if they are significant. Exception to this is noted for rainfall quantity on the Brandywine Creek in which the simple correlation coefficient is positive and highly significant; whereas, the regression coefficients are negative and less than highly significant. Intercorrelation among the independent variables is the cause of this change of sign and significance.

Based on data used in this analysis and the equations derived therefrom, water discharge proves to be the most important independent variable for describing variation of sediment transport in streams. The tendency is strong for the mean concentration of sediment (on a storm event basis) to increase with increasing volume of water discharge. The least important independent variable is rainfall quantity. The poor results obtained from using rainfall quantity may be attributed to the poor measure of this statistic to represent the true rainfall quantity on a storm-to-storm basis and to its high degree of intercorrelation with quantity of runoff.

The importance of other independent variables range between that of water discharge and rainfall quantity. The regression coefficient for time during the period of record is negative for nearly all equations and is significant for equations for the Brandywine Creek and James River Basins. Thus, there is an important sediment concentration reduction with time for the two basins and the possibility of decreasing concentration in other basins. Sediment concentration increases significantly with mean air temperature or time of year for all streams except for the Scantic River and the James River at Scottsville, Va. The range for a 50° change of temperature varies from about 0.5 log unit of concentration for the Hazel River down to about 0.2 log unit for the Brandywine Creek. An increase in ground-water runoff tends to correlate with a decrease in sediment movement. The coefficients for ground-water runoff · variable were not significant for the Hazel, Rappahannock, and Rapidan Rivers and generally not highly significant in other basins. Thus, the rate of ground-water flow as a measure of antecedent conditions is not as effective in explaining storm-to-storm sediment variation as expected.

The three measures of storm intensity: peakedness index, peak flow, and rainfall intensity, were not fully compared for all streams. Only peakedness index was determined for all streams. Sediment concentration of storm runoff in streams increases with each of these measures of storm intensity. Peakedness index resulted in a slightly lower standard error of estimate than peak flow for the Brandywine Creek, the Hazel River, and the two locations on the James River. Peakedness index is not considered significant for the Hazel River. Rainfall intensity was not significant for the Rapidan River. Measures of rainfall intensity were not available for testing in the James Basin. Comparison of rainfall intensity with the parameters based on peak flow, as a measure of the effect of storm intensity, shows that the relative standard error of estimate of the equations is not consistently higher or lower when rainfall intensity is used. The significance of the regression coefficients shown in table 8 indicate that either peakedness index or peak flow is a better measure of storm intensity than is rainfall intensity.

VARIATION AMONG BASINS

Differences in the regression coefficients for the independent variables among the several streams used in the analyses may indicate part of the difference in the characteristics of drainage basins to cause storm-to-storm variation in sediment movement. Table 8 shows that the standard error of estimate S_e varies some for a given basin depending on the combination of independent variables used in the regression. The variation of S_e for several combinations of variables at a given location, however, is small compared to that among basins.

The list of equations by basins for the single, double, and triple most significant independent variables (table 9) further demonstrates that even though S_e decreases somewhat as the number of variables is increased, there is a range of S_e among the basins. This is caused by either some error in the basic data or, more likely, the variance of hydrologic and environmental factors which cannot be evaluated at this time. Evidence from the list of equations of the effect of intercorrelation among the independent variables suggests that if one variable contained considerable error it would be replaced by another variable of greater significance. When this takes place, or when all variables except one or two remain, however, the error of estimate is not materially changed.

TABLE 9.—*The regression equations, by streams, for 1, 2, or 3 independent variables*

	One independent variable	
Scantic	Log $C=1.714+0.227 \log Q_b$	$S_e=0.144$
Brandywine	Log $C=1.255+.400 \log Q_w$	$S_e=.242$
Hazel	Log $C=1.563+.308 \log P_n$	$S_e=.311$
	Log $C=1.973+.0082\ T_a$	$S_e=.312$
Rappahannock	Log $C=2.193+.0054\ T_a$	$S_e=.267$
Rapidan	Log $C=1.702+.259 \log Q_w$	$S_e=.315$
James, Buchanan		
James, Scottsville	Log $C=0.683+0.425 \log P_n$	$S_e=.204$
	Two independent variables	
Scantic	Log $C=1.719+0.2106 \log Q_b+0.031\ P_i$	$S_e=0.142$
Brandywine	Log $C=.349+.582 \log Q_w+.239\ P_i$	$S_e=.220$
Hazel	Log $C=.809+.324 \log Q_w+.0115\ T_a$	$S_e=.273$
	Log $C=.704+.399 \log P_n+.0108\ T_a$	$S_e=.265$
	Log $C=1.576+.368 \log 10R_q+.0080\ T_a$	$S_e=.296$
Rappahannock	Log $C=1.280+.233 \log Q_w+.0078\ T_a$	$S_e=.246$
Rapidan	Log $C=.957+.335 \log Q_w+.0091\ T_a$	$S_e=.289$
James, Buchanan	Log $C=1.352+.203 \log Q_w-.0038\ M_t$	$S_e=.308$
James, Scottsville	Log $C=1.129-.211 \log Q_b+.496 \log P$	$S_e=.198$
	Three independent variables	
Scantic	Log $C=1.532+0.082 \log Q_w+0.200 \log Q_b+0.035\ P_i$	$S_e=0.139$
Brandywine	Log $C=.122+.606 \log Q_w+.0038\ T_a+.208\ P_i$	$S_e=.313$
Hazel	Log $C=.462+.391 \log Q_w+.0106\ T_a+.304\ P_i$	$S_e=.268$
	Log $C=.554+.291 \log Q_w+.0086\ T_a+.441 \log 100R_i$	$S_e=.260$
	Log $C=.719-.0018\ M_t+.0112\ T_a+.402 \log P_n$	$S_e=.266$
Rappahannock	Log $C=1.373+.232 \log Q_w-.0021\ M_t+.0079\ T_a$	$S_e=.240$
Rapidan	Log $C=1.035+.327 \log Q_w-.0027\ M_t+.0094\ T_a$	$S_e=.286$
James, Buchanan	Log $C=.036+.373 \log Q_w-.0043\ M_t+.0117\ T_a$	$S_e=.278$
James, Scottsville	Log $C=1.271-.0029\ M_t-.262 \log Q_b+.525 \log P_n$	$S_e=.192$

EXAMPLES OF APPLICATION

RANGE OF SPECIFIC VARIABLES

The multiple regression equations determined in this analysis consists of an equation constant and coefficients for each independent variable. Each independent variable may affect the dependent variable through its range of values depending on the magnitude of the coefficient. One of the equations determined for the James River at Buchanan, Va. (see table 8) will be used to demonstrate this effect.

$$\text{Log } C=0.960+0.532 \log Q_w-0.0053\ M_t+0.00777\ T_a -0.556 \log Q_b+1.019\ P_t.$$

The following realistic minimum and maximum values of the variables are applied:

$Q_w=1{,}000$ and $100{,}000$ cfs-days; $\log Q_w=3.00$ and 5.00

$M_t=1$ and 65 months

$T_a=35°$ and $75°$F

$Q_b=316$ and $3{,}160$ cfs; $\log Q_b=2.5$ and 3.5

$P_t=0.19$ and 0.64

$$\text{Log } C\ (\text{max})=+0.960+2.659-0.344+0.583-1.943+0.652$$

$$=+2.567\pm0.230 \text{ or } C=369 \text{ ppm ranging from 217 to 626 ppm.}$$

$$\text{Log } C\ (\text{min})=+0.960+1.594-0.005+0.272-1.388+0.194$$

$$=+1.627\pm0.230 \text{ or } C=42 \text{ ppm ranging from 25 to 72 ppm.}$$

The differences between the maximum and minimum factors for these equations are +1.065, −0.339, +0.311, −0.555, and +0.458 log units for Q_w, M_t, T_a, Q_b, and P_t, respectively. These differences are all greater than S_e or 0.230 log units, and therefore, further indicate that these factors all yield a significant change in the dependent variable.

COMPARISON OF LOCATIONS

For comparing the regression equations between locations, the mean values of the independent variables will be used (see table 5) to compute the value of the dependent variable. The simplest comparison can be made by use of the equations for one and three independent variables as given in table 9.

For the single variable on the Brandywine Creek:

$$\text{Log } C=+1.255+0.400 \log Q_w$$

$$=+1.255+0.400\times3.161$$

$$=+2.520\pm0.242$$

This is an average of 331 ppm or a range from 190 to 578 ppm.

For the Rapidan River:

$$\text{Log } C=+1.702+0.259 \log Q_w$$

$$=+1.702+0.259\times3.234$$

$$=+2.540\pm0.315$$

This is a mean of 347 ppm or a range from 168 to 716 ppm. The regression slope of log Q_w is 0.400 for the Brandywine and 0.259 for the Rapidan, yet the mean concentration is nearly the same, due somewhat to the higher mean of log Q_w for the Rapidan, but mostly due to the greater equation constant for the Rapidan.

For the three independent variables on the Brandywine Creek:

$$\text{Log } C=0.122+0.606 \log Q_w+0.0038\ T_a+0.208\ P_t$$

$$=0.122+0.606\times3.161+0.0038\times50.93+0.208\times1.383$$

$$=2.518\pm0.213$$

This is a mean of 329 ppm or a range from 202 to 538 ppm.

For the Hazel River:

$$\text{Log } C=+0.462+0.391 \log Q_w+0.0106\ T_a+0.304\ P_t$$

$$=+0.462+0.391\times3.016+0.0106\times55.63+0.304\times0.650$$

$$=+2.426\pm0.268$$

This is a mean of 267 ppm or a range from 144 to 494 ppm. Comparison of the latter more complicated equations with the single variable equations shows that the Brandywine has the greater Q_w and P_t factors and that the Hazel has the greatest equation constant and T_a factors but the totals differ by less than 0.1 log unit. Note that the range defined by the limits of S_e is considerably less when three variables instead of one are used.

EXTRAPOLATION TO OTHER STREAMS

In order to demonstrate the feasibility of applying the computed regression formulas to other streams, testing with observed data from some other locations is necessary. Observed data are available for 15 storms on the Shenandoah River at Front Royal, Va., (1,638 sq mi) and for 14 storms on the Potomac River at Point of Rocks, Md., (9,650 sq mi). The Shenandoah data were obtained during the same period, and the Potomac data were obtained 7 or 8 years later than the data from which the models were derived. The Potomac River data, in addition to a somewhat different time span, also represent a much larger and more diverse basin than that from which the models were derived. The data are listed in table 10. The following are equations from the appendix for testing these data:

1. III–3 from the Brandywine Creek,

$$\text{Log } C=+0.181+0.610 \text{ log } Q_w-0.00139M_t +0.00390T_a+0.214P_t—(0.208)$$

2. III–2 from the Rappahannock River,

$$\text{Log } C=+1.059+0.289 \text{ log } Q_w-0.00190M_t +0.00760T_a+0.199P_t—(0.239)$$

3. IV from the James River at Buchanan, Va.,

$$\text{Log } C=-0.649+0.454 \text{ log } Q_w-0.00333M_t +0.01175T_a+0.769P_t—(0.269).$$

TABLE 10.—*Measured data for extrapolation of models to other streams*

Observation No.	Log C	Log Q_w	M_t	T_a	P_i
Shenandoah River					
1	1.88	3.72	34	38	0.65
2	2.81	4.53	35	41	.59
3	2.04	3.63	35	49	.90
4	2.39	4.18	38	73	.25
5	2.99	4.49	42	58	.52
6	2.25	4.39	43	44	.32
7	2.35	4.27	44	37	.53
8	2.38	4.21	46	39	.39
9	2.66	4.59	47	46	.27
10	2.40	4.16	47	50	.47
11	1.97	3.94	48	58	.41
12	2.05	3.68	48	59	.48
13	2.49	4.45	50	72	.20
14	2.58	4.45	52	75	.56
15	2.97	5.16	52	74	.43
Potomac River					
1	2.68	4.65	102	62	0.59
2	2.23	4.58	105	37	.71
3	2.90	5.41	107	52	.38
4	2.61	5.31	108	53	.51
5	2.77	5.29	109	63	.64
6	2.30	4.87	109	69	.60
7	2.92	5.34	117	41	.47
8	2.65	5.24	117	42	.53
9	2.29	5.30	119	55	.40
10	2.34	5.10	119	57	.52
11	1.90	4.13	120	63	1.29
12	2.11	4.73	120	67	.54
13	2.38	3.99	121	72	1.08
14	2.22	4.28	125	55	.77

The computed sediment concentration derived for each storm and for each model was plotted against the observed concentration in figures 19 and 20 for the Shenandoah and Potomac Rivers, respectively. The results show that:

1. None of the applications are reasonably close to the line of agreement; and, therefore, it is extremely dangerous to extend specific formulas to other basins.
2. The size of the river basin determines the shift of the computed values from the observed values. The model from the smallest stream (Brandywine Creek) yields results that are about 0.6 log unit too large when the Shenandoah data are used and about 0.9 log unit too large when the Potomac data are used. Also, the data from the larger Potomac River basin yield computed values for the three formulas that average about 0.2 log unit greater than data from the Shenandoah.
3. The concentrations computed from the models do not increase as rapidly as the observed concentrations. The Brandywine formula is not as serious in this respect as are the Rappahannock and James River formulas.

Although a given formula apparently cannot be extrapolated to another stream, the hypothesis that the general model can be extrapolated is still open. Thus, assuming that the observed data for the Shenandoah and Potomac are statistically representative, trial and error modification of the James River and Brandywine Creek formulas was made to shift the computed concentration. Shifting the set of computed values up and down on the ordinate of figures 19 and 20 is accomplished by adjusting the equation constant. Change in the slope and scatter of the set is accomplished by shifting the emphasis on Q_w or P_t. Due to the proximity of the James River and Brandywine Creek basins to the Shenandoah and Potomac River basins, there is little justification for altering the factors for M_t and T_a.

To accommodate the conditions exhibited by the Shenandoah River data, the equation constant and the coefficients for log Q_w and P_t in the James River formula were changed by trial and error to a modified formula,

$$\text{Log } C=-0.600+0.600 \text{ log } Q_w-0.00333\ M_t +0.01175\ T_a+0.200\ P_t.$$

The James River formula was also changed to accommodate the Potomac River data to

$$\text{Log } C=-0.800+0.600 \text{ log } Q_w-0.00333\ M_t +0.01175\ T_a.$$

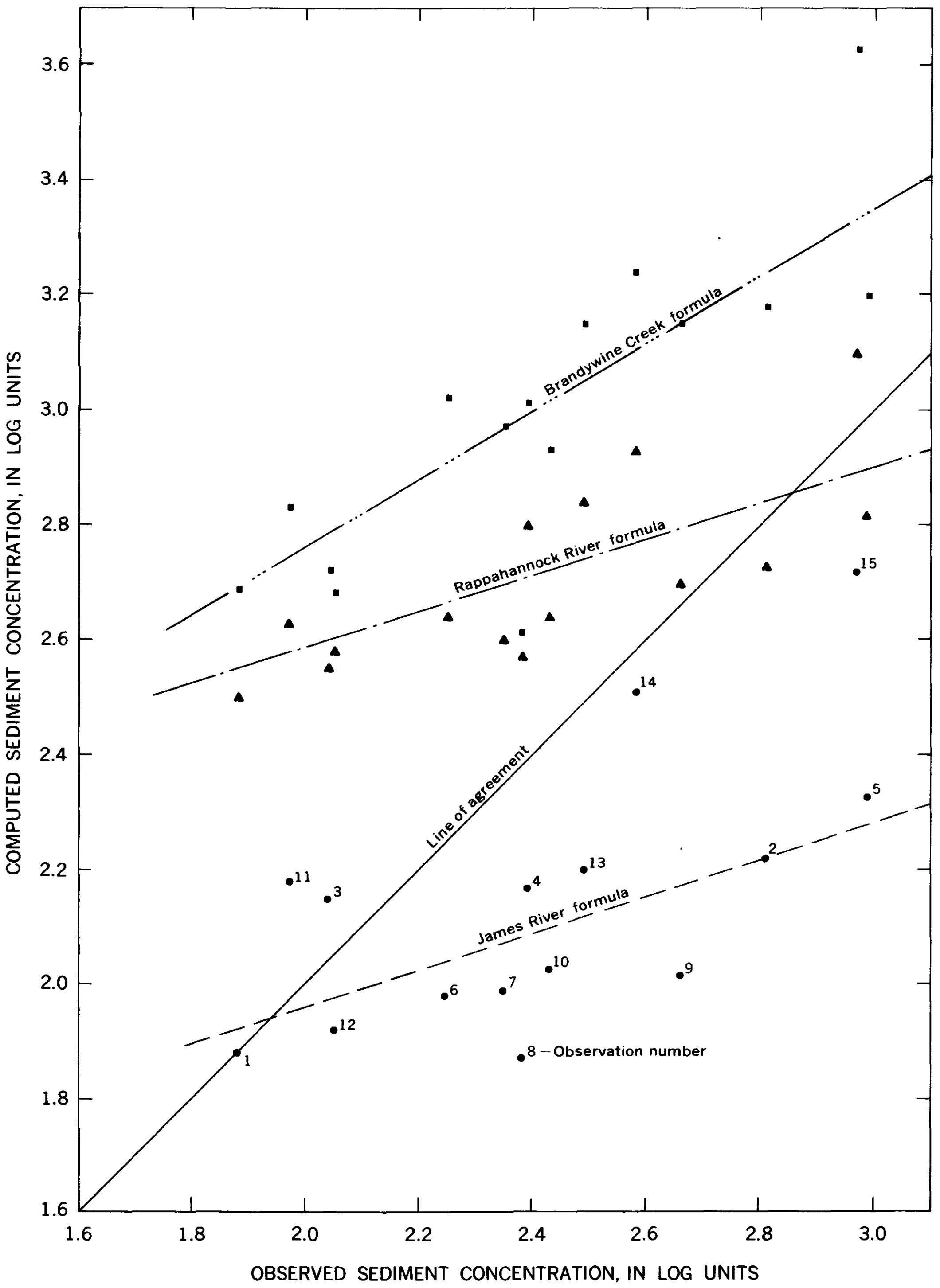


FIGURE 19.—Test of selected models against observed data for Shenandoah River.

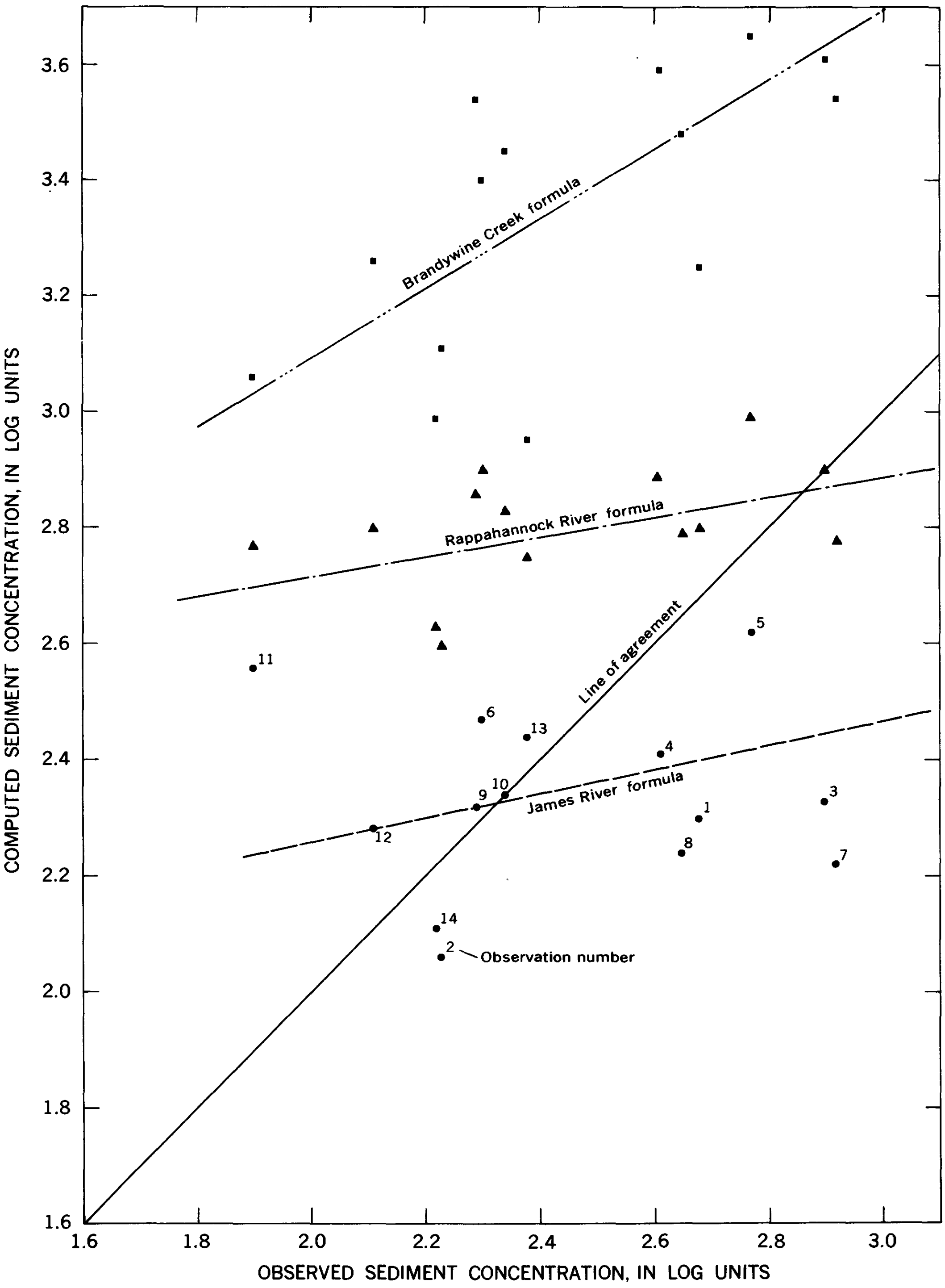


FIGURE 20.—Test of selected models against observed data for Potomac River.

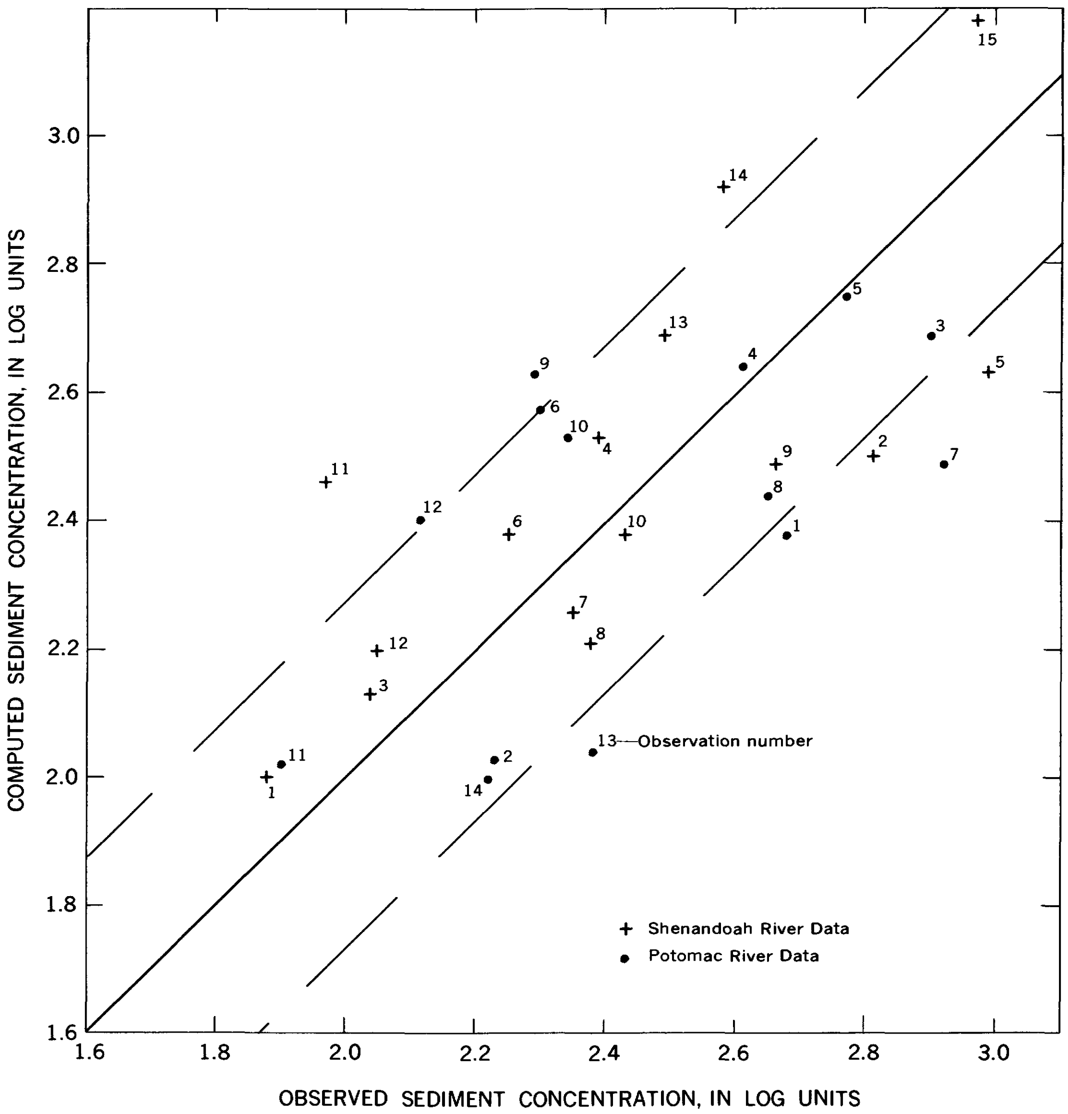


FIGURE 21.—Comparison of the modified formula for James River at Buchanan with the observed data for the Shenandoah and Potomac Rivers.

Figure 21 compares the computed sediment concentration from each modified formula with their respective observed sediment concentrations. The results of the comparison are reasonable in that the computed values are sufficiently close to the line of agreement so that all but 4 out of 15 for the Shenandoah River and all but 5 out of 14 points for the Potomac River are within the standard error of estimate (0.269 log units) defined by the original James River model.

In a like manner, the Brandywine Creek formula was changed to

$$\text{Log } C = -0.700 + 0.700 \log Q_w - 0.00139\, M_t + 0.00390\, T_a$$

to accommodate the Shenandoah River data; and to

$$\text{Log } C = -0.970 + 0.700 \log Q_w - 0.00139\, M_t + 0.00390\, T_a$$

to accommodate the Potomac River data. Comparison of the computed values from these modified formulas with the observed data (fig. 22) is within the standard error of estimate (0.208 log units) defined by the original Brandywine model.

The similarity of the two modified models is indicated by the similarity of the deviations from the line of agreement with respect to the individual storms. For example, in figures 21 and 22, note that observations 2 and 5 for the Shenandoah and 1 and 13 for the Potomac plot below the limits of one S_e.

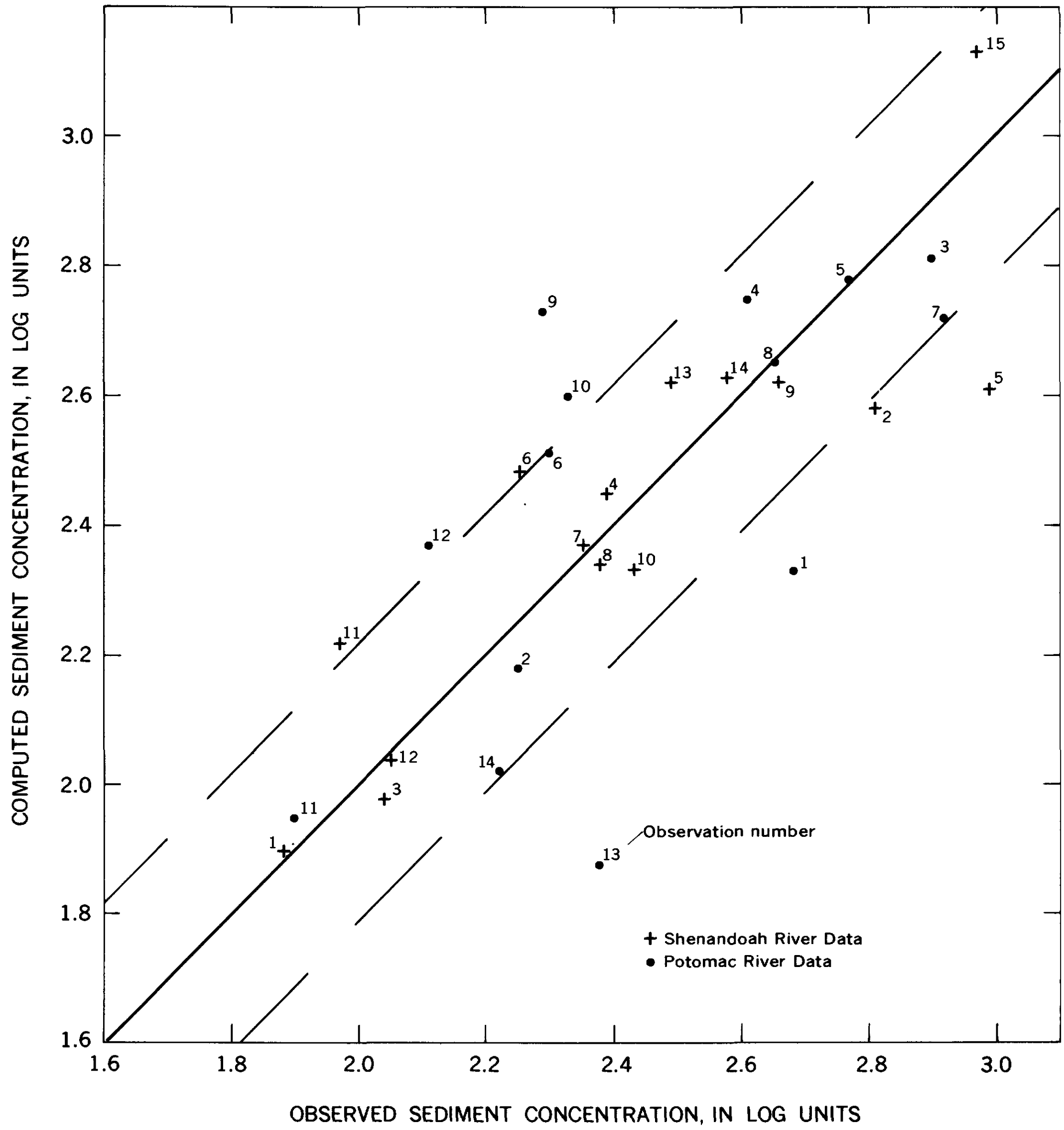


FIGURE 22.—Comparison of the modified formula for Brandywine Creek with the observed data for the Shenandoah and Potomac Rivers.

SUMMARY

The analysis of some storm period variables affecting stream sediment transport has involved a study of available sediment data to determine which hydrologic, physical, and biological factors cause sediment variation in time and space. The knowledge gained from this and other similar analyses can be used to interpret and extrapolate the small amount of information available from existing or reconnaissance sediment data.

A review of the theory of sediment yield and transport shows that most of the fine sediment (clay and silt sizes) eroded from a drainage basin is easily suspended by the stream turbulence and hence readily moved through the channel system; whereas, the coarser sediment (sands, gravels) are moved in accordance with the interaction of the stream energy on the particle and the settling rate of the particles. The amount of coarse sediment transported is generally much less than half the total sediment discharge. The coarse sediment discharge can be approximately determined by considering hydraulic factors; such considerations are beyond the scope of this report. The most important variables for consideration in the analysis involve the forces of erosion and transport as related to fine sediment.

These forces operate during or immediately following periods of substantial precipitation and runoff from the land surface, thus the adopted hydrologic unit for study in this report is the storm event. Subsurface and ground-water runoff are not important erodents of the land surface; therefore, only the surface runoff part of the hydrograph is used.

Analysis of data to determine the cause of sediment variation was accomplished by a combination of graphical and analytical multiple regression methods. Graphical correlation was necessary to determine which variable to consider, to determine the required transformation of the data, and to note unusual elements of the relationship. Using the general regression model

$$Y=b_o+b_1x_1+b_2x_2+\ .\ .\ .\ +b_nx_n,$$

the analytical method was then used to obtain the best estimate of the equation coefficients and their significance and the standard error of the equation. The analysis was made using data for seven stream locations in the Atlantic coast area through a program developed for the Burroughs 220 computer.

The graphical search for variables useful to explain the variation of sediment concentration or discharge from storm to storm showed that:

1. The month during the period of record may be used to indicate the trend of change of time.
2. The quantity of surface runoff, expressed in log units, should be used as a measure of the magnitude and intensity of erosion and transport—precipitation quantity, also in log units, is not as effective.
3. The long-term mean air temperature for the time of year of the given storm can be used as a measure of seasonal change.
4. Ground-water runoff of the stream prior to storm runoff, expressed in log units, is a convenient measure of antecedent conditions.
5. The peakedness of the storm hydrograph can be used as a measure of storm intensity. Precipitation intensity, expressed in log units, is sometimes too difficult to evaluate and too inaccurately determined for an effective measure of storm intensity.

The computer program is designed to print out simple correlation coefficients and their significance. These indicate the degree of intercorrelation among the variables for a given set of storm-period data at a stream location. In general terms, the correlations show a tendency for:

1. The mean concentration of sediment in the storm runoff to increase with sediment discharge, water discharge, air temperature, peak flow, rainfall quantity, and rainfall intensity.
2. The quantity of sediment discharge to increase with water discharge, peak flow, rainfall quantity, and rainfall intensity, and to decrease with peakedness index.
3. The quantity of water discharge per storm event to increase with ground-water runoff, peak flow, and rainfall quantity, and to decrease with air temperature and peakedenss index.
4. The ground-water runoff to increase with peak flow and to decrease with time during the period of record, air temperature, peakedness index, rainfall quantity, and rainfall intensity.
5. The peak flow to increase with rainfall quantity.
6. The rainfall quantity to increase with rainfall intensity.

Comparison of log Q_s (sediment discharge) and log C (sediment concentration) for use as the dependent variable in the analytical computation of the multiple regression equation was completed for the Hazel River and Brandywine Creek. The two most important conclusions from this comparison are: (1) the standard error of estimate is less for log C than for log Q_s but not appreciably so; (2) when log Q_s is used, the very high degree of significance for log Q_w causes a decrease of significance for the remaining independent variables.

It was noted from the regression equations that variation of coefficients for a specific variable at a specific stream location, when different sets of variables are used, is largely due to the effects of intercorrelation among the variables. In regard to a measure of storm size, water discharge proves to be the most important independent variable for describing sediment variation, and rainfall quantity is generally the least important. The poor significance of rainfall quantity is probably due to the poor quality of available data and its high degree of intercorrelation with quantity of runoff and other hydrologic factors.

The regression coefficients for time during the period of record show a reduction of sediment concentration with time for nearly all sets of variables. This reduction is statistically significant for the locations on the Brandywine Creek and the James River basins.

The equations show that sediment concentration increases significantly with mean air temperature or time of the year for all streams except the Scantic and the James River at Scottsville.

Although the regression coefficients for ground-water runoff were not significant for the Hazel, Rappahannock, and Rapidan Rivers and not highly significant in other basins, the sediment concentration tends to decrease as ground-water runoff increases.

Of the three measures of storm intensity, only peakedness index was determined for all streams. Sediment in streams tends to increase with each of measures of storm intensity.

The standard error of estimate for the equations varies much more among the different streams than among the different combinations of variables for a given stream. This is caused by the variance of hydrologic and environmental factors not evaluated by the data used, or possibly by some error in the basic data. The standard error of estimate ranges from 0.14 to 0.30 of a log unit for most computed combinations of variables.

Three of the regression formulas were tested with observed data from 15 storm events on the Shenandoah River at Front Royal, Va., and from 14 storm events on the Potomac River at Point of Rocks, Md. The results indicated four points of interest: (1) None of the computed concentration values were consistently close to agreement with the observed values. (2) The relative size of the river basin determines the shift of the computed values from the observed values. (3) The ratio of the computed to the measured values decreases as the observed values increase. (4) The formulas can be modified to yield computed values in good agreement with the observed values.

RECOMMENDATIONS

Although the analysis of data for seven stream locations in the Atlantic coast area using several combinations of variables yields formulas for predicting sediment transport, it is apparent that extrapolation to basins of different sizes and locations is not practical at this stage.

Four areas of further study are apparent:

1. Continue the search for suitable independent variables and their proper transformation. This would further explain the storm-to-storm variation for specific stream locations.
2. Determine the effect of the number of storm events on the equation and its significance for at least three stream locations.
3. Reduce to dimensionless terms the data that is affected by drainage basin size. This would include such variables used in this study as sediment discharge Q_s, water discharge Q_w, ground-water runoff Q_b, and peak flow P_n.
4. Extend the work to other stream locations to encompass environments of considerably different climate, soil characteristics, topography, vegetative cover, drainage density, and drainage basin size. Measures of these characteristics on a stream location basis must be developed.

The results of such studies will help to advance progress toward development of a "universal equation" for computing stream sediment transport through application of specific observed variables.

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APPENDIX

MULTIPLE REGRESSION EQUATIONS

This appendix contains regression equations for seven stream locations in the Atlantic coast area and for selected combinations of variables used in the analyses to show the effect of these variables in predicting sediment conditions on the basis of storm events. The relative value of each equation is indicated by the standard error of estimate of the dependent variable in terms of log units. This is shown in parentheses at the end of each equation. The significance of the regression coefficients is indicated by superscript as follows:

a. Very highly significant (99.9 percent level).
b. Highly significant (99 percent level).
c. Significant (95 percent level).
d. Poorly significant (90 percent level).
e. Very poorly significant (80 percent).

Where a superscript is not shown with a coefficient, the variable cannot be considered useful in explaining sediment variation. Such a variable, however, cannot be dropped from a specific equation without adjustment to coefficients of other variables.

SCANTIC RIVER NEAR BROAD BROOK, CONNECTICUT

Surface runoff—65 storm events

I. Log *C* is dependent variable

1. $\mathrm{Log}\ C=1.548+0.151^{\mathrm{c}}\log Q_w-0.00001\ \mathrm{M}_t+0.00115\ T_a+0.163^{\mathrm{c}}\log Q_b+0.036^{\mathrm{c}}\ P_i-0.138^{\mathrm{e}}\log 10\ R_q \quad S_e=0.140$
2. $\mathrm{Log}\ C=1.547+0.151^{\mathrm{c}}\log Q_w+0.00114\ \mathrm{T}_a+0.163^{\mathrm{c}}\log Q_b+0.036^{\mathrm{c}}\ P_i-0.138^{\mathrm{d}}\log 10\ R_q \quad S_e=0.138$
3. $\mathrm{Log}\ C=1.551+0.143^{\mathrm{c}}\log Q_w+0.177^{\mathrm{c}}\log Q_b+0.037^{\mathrm{c}}\ P_i-0.113^{\mathrm{e}}\log 10\ R_q \quad S_e=0.138$
4. $\mathrm{Log}\ C=1.532+0.082^{\mathrm{d}}\log Q_w+0.200^{\mathrm{b}}\log Q_b+0.035^{\mathrm{c}}\ P_i \quad S_e=0.139$
5. $\mathrm{Log}\ C=1.719+0.211^{\mathrm{b}}\log Q_b+0.0314^{\mathrm{d}}\ P_i \quad S_e=0.142$
6. $\mathrm{Log}\ C=1.714+0.227^{\mathrm{b}}\log Q_b \quad S_e=0.144$

II

1. $\mathrm{Log}\ C=1.516+0.135^{\mathrm{c}}\log Q_w-0.00021\ M_t+0.00121\ T_a+0.190^{\mathrm{c}}\log Q_b-0.153^{\mathrm{d}}\log 10\ R_q+0.065\log 100\ R_t \quad S_e=0.144$
2. $\mathrm{Log}\ C=1.492+0.135^{\mathrm{c}}\log Q_w+0.00112\ T_a+0.196^{\mathrm{c}}\log Q_b-0.149^{\mathrm{e}}\log 10\ R_q+0.068\log 100\ R_t \quad S_e=0.143$
3. $\mathrm{Log}\ C=1.567+0.135^{\mathrm{c}}\log Q_w+0.00138\ T_a+0.182^{\mathrm{c}}\log Q_b-0.132^{\mathrm{e}}\log R_q \quad S_e=0.142$
4. $\mathrm{Log}\ C=1.572+0.125^{\mathrm{c}}\log Q_w+0.200^{\mathrm{b}}\log Q_b-0.102^{\mathrm{e}}\log 10\ R_q \quad S_e=0.142$
5. $\mathrm{Log}\ C=1.553+0.070^{\mathrm{e}}\log Q_w+0.219^{\mathrm{b}}\log Q_b \quad S_e=0.143$
6. $\mathrm{Log}\ C=1.714+0.227^{\mathrm{b}}\log Q_b \quad S_e=0.144$

Total runoff—65 storm events

III

1. $\mathrm{Log}\ C=0.033+0.502^{\mathrm{a}}\log Q_w-0.00100M_t+0.00019T_a-0.208^{\mathrm{d}}\log Q_b+1.202^{\mathrm{a}}P_t \quad S_e=0.179$
2. $\mathrm{Log}\ C=0.031+0.503^{\mathrm{a}}\log Q_w-0.00102M_t-0.206^{\mathrm{c}}\log Q_b+1.205^{\mathrm{a}}P_t \quad S_e=0.177$
3. $\mathrm{Log}\ C=0.134+0.487^{\mathrm{a}}\log Q_w-0.216^{\mathrm{c}}\log Q_b+1.225^{\mathrm{a}}P_t \quad S_e=0.177$
4. $\mathrm{Log}\ C=0.090+0.398^{\mathrm{a}}\log Q_w+1.387^{\mathrm{a}}P_t \quad S_e=0.178$
5. $\mathrm{Log}\ C=1.259+1.155^{\mathrm{a}}P_t \quad S_e=0.213$

IV

1. $\mathrm{Log}\ C=0.024+0.415^{\mathrm{a}}\log Q_w+0.00131M_t-0.00104T_a-0.127\log Q_b+1.171^{\mathrm{a}}P_t+0.142^{\mathrm{e}}\log 10R_q \quad S_e=0.178$
2. $\mathrm{Log}\ C=0.034+0.423^{\mathrm{a}}\log Q_w+0.00120M_t-0.148^{\mathrm{e}}\log Q_b+1.159^{\mathrm{a}}P_t+0.121^{\mathrm{e}}\log 10R_q \quad S_e=0.177$
3. $\mathrm{Log}\ C=0.154+0.412^{\mathrm{a}}\log Q_w-0.166^{\mathrm{e}}\log Q_b+1.187P_t+0.109\log 10R_q \quad S_e=0.178$
4. $\mathrm{Log}\ C=0.134+0.488^{\mathrm{a}}\log Q_w-0.216^{\mathrm{c}}\log Q_b+1.225^{\mathrm{a}}P_t \quad S_e=0.178$
5. $\mathrm{Log}\ C=1.259+1.155^{\mathrm{a}}P_t$

V

1. $\mathrm{Log}\ C=0.267+0.404^{\mathrm{b}}\log Q_w+0.00181^{\mathrm{e}}\ M_t-0.00138\ T_a-0.184^{\mathrm{e}}\log Q_b+0.105\log 10\ R_q+0.0256^{\mathrm{e}}\log 100\ R_t \quad S_e=0.200$
2. $\mathrm{Log}\ C=0.311+0.412^{\mathrm{b}}\log Q_w+0.000165^{\mathrm{e}}\ M_t-0.214^{\mathrm{d}}\log Q_b+0.086\log 10\ R_q+0.225^{\mathrm{e}}\log 100\ R_t \quad S_e=0.199$
3. $\mathrm{Log}\ C=0.241+0.460^{\mathrm{a}}\log Q_w+0.00157^{\mathrm{e}}\ M_t-0.239^{\mathrm{c}}\log Q_b+0.290^{\mathrm{c}}\log 100\ R_t \quad S_e=0.198$
4. $\mathrm{Log}\ C=0.435+0.438^{\mathrm{a}}\log Q-0.263^{\mathrm{c}}\log Q_b+0.275^{\mathrm{d}}\log 100\ R_t \quad \mathrm{S}_e=0.200$
5. $\mathrm{Log}\ C=0.768+0.481^{\mathrm{a}}\log Q_w-0.341^{\mathrm{b}}\log Q_b \quad S_e=0.204$
6. $\mathrm{Log}\ C=0.527+0.327^{\mathrm{a}}\log Q_w \quad S_e=0.217$

Total runoff—136 storm events

[Rainfall data not available]

VI

1. $\mathrm{Log}\ C=0.549+0.695^{\mathrm{a}}\log Q_w+0.00128\ M_t+0.00147\ \mathrm{T}_a-0.318^{\mathrm{b}}\log Q_b+1.42^{\mathrm{a}}\ P_t \quad S_e=0.2387$
2. $\mathrm{Log}\ C=-0.480+0.683^{\mathrm{a}}\log Q_w+0.00132\ M_t-0.311^{\mathrm{b}}\log Q_b+1.461^{\mathrm{a}}\ P_t \quad S_e=0.239$
3. $\mathrm{Log}\ C=-0.375+0.672^{\mathrm{a}}\log Q_w-0.325^{\mathrm{b}}\log Q_b+1.472^{\mathrm{a}}\ P_t \quad S_e=0.239$
4. $\mathrm{Log}\ C=-0.677+0.538^{\mathrm{a}}\log Q_w+1.56^{\mathrm{a}}\ P_t \quad S_e=0.247$
5. $\mathrm{Log}\ C=0.558+0.285^{\mathrm{a}}\log \mathrm{Q}_w \quad S_e=0.279$

BRANDYWINE CREEK AT WILMINGTON, DELAWARE

Surface runoff—138 storm events

I

1. $\text{Log } C=0.886+0.644^{a}\log Q_w-0.00155^{b} M_t+0.00385^{e}\mathrm{T}_a-0.195^{c}\log Q_b-0.365^{c}\log 10\, R_q+0.338^{b}\log 100\, R_i \quad S_e=0.215$
2. $\text{Log } C=0.450+0.559^{a}\log Q_w-0.00137^{c} M_t+0.0038^{c} T_a-0.208^{e}\log 10\, R_q+0.368^{b}\log 100\, R_i \quad S_e=0.218$
3. $\text{Log } C=0.611+0.452^{a}\log Q_w-0.00136^{c} M_t+0.00241^{d} T_a+0.353^{b}\log 100\, R_i \quad S_e=0.219$
4. $\text{Log } C=0.674+0.429^{a}\log Q_w-0.00137 M_t+0.463^{a}\log 100\, R_i \quad S_e=0.220$
5. $\text{Log } C=0.610+0.430^{a}\log Q_w+0.446^{a}\log 100\, R_i \quad S_e=0.224$
6. $\text{Log } \mathrm{C}=1.255+0.400^{a}\log Q_w \quad S_e=0.241$

II

1. $\text{Log } \mathrm{C}=1.039+0.325^{c}\log Q_w-0.00199^{a} M_t+0.00554^{a} T_a-0.183^{c}\log Q_b+0.333^{a}\log P_n-0.274^{d}\log 10\, R_q \quad S_e=0.211$
2. $\text{Log } C=1.029+0.166^{d}\log Q_w-0.00195^{a} M_t+0.00431^{a} T_a-0.109_{e}\log Q_b+0.352^{a}\log P_n \quad S_e=0.213$
3. $\text{Log } C=0.731+0.155^{d}\log Q_w-0.00186^{b} M_t+0.00462^{a} T_a+0.363^{a}\log P_n \quad S_e=0.213$
4. $\text{Log } C=0.859-0.00208^{a} M_t+0.00411^{a} T_a+0.486^{a}\log P_n \quad S_e=0.215$
5. $\text{Log } C=1.163-0.00194^{b} M_t+0.454^{a}\log P_n \quad S_e=0.224$
6. $\text{Log } C=1.120+0.432^{a}\log P_n \quad S_e=0.232$

III

1. $\text{Log } \mathrm{C}=0.406+0.719^{a}\log Q_w-0.00150^{b}M_t+0.00484^{a}T_a-0.124^{e}\log \mathrm{Q}_b+0.196^{a}\mathrm{P}_1=0.232^{e}\log 10\, \mathrm{R}_q \quad S_e=0.208$
2. $\text{Log } C=0.958+0.674^{a}\log Q_w-0.00139^{c} M_t+0.00457^{a} T_a+0.212^{a} P_i-0.127\log 10\, \mathrm{R}_q \quad S_e=0.208$
3. $\text{Log } C=0.181+0.610^{a}\log Q_w-0.00139^{c} M_t+0.00390^{a} T_a+0.214^{a} P_i \quad S_e=0.208$
4. $\text{Log } C=0.121+0.606^{a}\log Q_w+0.00382^{b} T_a+0.208^{a} P_i \quad S_e=0.213$
5. $\text{Log } C=0.349+0.582^{a}\log Q_w+0.239^{a} P_i \quad S_e=0.220$
6. $\text{Log } C=1.255+0.400^{a}\log Q_w \quad S_e=0.241$

IV

1. $\text{Log } Q_s=-1.634+1.633^{a}\log Q_w-0.00142^{c} M_t+0.00365^{c} T_a-0.199^{c}\log Q_b-0.354^{c}\log 10\, R_q+0.328_{b}\log 100\, R_i \quad S_e=0.216$
2. $\text{Log } Q_s=-2.079+1.546^{a}\log Q_w-0.00123^{c} M_t+0.00317^{d} T_a-0.194^{e}\log 10\, R_q+0.359^{b}\log 100\, R_i \quad S_e=0.219$
3. $\text{Log } Q_s=-1.929+1.445^{a}\log Q_w-0.00123^{c} M_t+0.00227^{e} T_a+0.346^{b}\log 100\, R_i \quad S_e=0.220$
4. $\text{Log } Q=-1.870+1.425^{a}\log Q_w-0.00123^{c} M_t+0.448^{a}\log 100\, R_i \quad S_e=0.221$
5. $\text{Log } Q=-1.928+1.426^{a}\log Q_w+0.448^{a}\log 100\, R_i \quad S_e=0.224$
6. $\text{Log } Q=-1.320+1.397^{a}\log Q_w \quad S_e=0.240$

V

1. $\text{Log } Q_s=-1.494+1.310^{a}\log Q_w-0.00187^{b} M_t+0.00526^{a} T_a-0.185^{c}\log Q_b+0.336^{a}\log P_n-0.262^{e}\log 10\, R_q \quad S_e=0.212$
2. $\text{Log } Q_s=-1.504+1.158^{a}\log Q_w-0.00183^{b} M_t+0.00408^{a} T_a-0.144^{e}\log Q_b+0.355^{a}\log P_n \quad S_e=0.213$
3. $\text{Log } Q_s=-1.817+1.147^{a}\log Q_w-0.00174^{b} M_t+0.00441^{a} T_a+0.366^{a}\log P_n \quad S_e=0.214$
4. $\text{Log } Q_s=-1.884+1.205^{a}\log Q_w+0.00438^{a} T_a+0.298^{a}\log P_n \quad S_e=0.221$
5. $\text{Log } Q_s=-1.744+1.459^{a}\log Q_w+0.0049^{a} T_a \quad S_e=0.229$
6. $\text{Log } Q_s=-1.302+1.397^{a}\log Q_w \quad S_e=0.241$

VI

1. $\text{Log } Q_s=-2.095+1.705^{a}\log Q_w-0.00137^{c} M_t+0.00462^{b} T_a-0.131^{e}\log Q_b+0.189^{a} P_t-0.225^{e}\log 10\, R_q \quad S_e=0.210$
2. $\text{Log } Q_s=-2.141+1.596^{a}\log Q_w-0.00131^{c} M_t+0.00358^{b} T_a-0.667\log Q_b+0.200^{a} P_i \quad S_e=0.211$
3. $\text{Log } Q_s=-2.345+1.600^{a}\log Q_w-0.00125^{c} M_t+0.00374^{b} T_a+0.208^{a} P_i \quad S_e=0.211$
4. $\text{Log } Q_s=-2.399+1.597^{a}\log Q_w-0.00366^{b} M_t+0.202^{a} P_t \quad S_e=0.214$
5. $\text{Log } Q_s=-2.180+1.574^{a}\log Q_w+0.232^{a} P_i \quad S_e=0.221$
6. $\text{Log } Q_s=-1.302+1.397^{a}\log Q_w \quad S_e=0.241$

HAZEL RIVER NEAR RIXEYVILLE, VA.

Surface runoff—75 storm events

I

1. $\text{Log } C=+0.660+0.474^{a}\log Q_w-0.00289 M_t+0.00153^{a} T_a-0.105\log Q_b+0.258^{e} P_i-0.149\log 10\, R_q \quad S_e=0.271$
2. $\text{Log } C=0.586+0.397^{a}\log Q_w-0.00242 M_t+0.01101^{a} T_a-0.040\log Q_b+0.278^{e} P_i \quad S_e=0.270$
3. $\text{Log } C=0.470+0.396^{a}\log Q_w-0.00199 M_t+0.01104^{a} T_a+0.311^{d} P_i \quad S_e=0.268$
4. $\text{Log } C=0.462+0.391^{a}\log Q_w+0.01057^{a} T_a+0.304^{d} P_t \quad S_e=0.268$
5. $\text{Log } C=0.809+0.324^{a}\log Q_w+0.01148^{a} T_a \quad S_e=0.273$
6. $\text{Log } C=1.973+0.00815^{a} T_a \quad S_e=0.312$

II

1. Log $C=+0.642+0.513^{a}\log Q_w-0.00256\,M_t+0.00970^{a}\,T_a-0.178^{e}\log Q_b-0.421^{c}\log 10\,R_q+0.533^{a}\log 100\,R_t \qquad S_e=0.255$
2. Log $C=+0.524+0.482^{a}\log Q_w+0.00909^{a}\,T_a-0.124\log Q_b-0.390^{c}\log 10\,R_q+0.554^{a}\log 100\,R_t \qquad S_e=0.255$
3. Log $C=+0.362+0.394^{a}\log Q_w+0.00918^{a}\,T_a-0.251^{e}\log 10\,R_q+0.551^{a}\log 100\,R_t \qquad S_e=0.256$
4. Log $C=0.554+0.291^{a}\log Q_w+0.00864^{a}\,T_a+0.441^{b}\log 100\,R_i \qquad S_e=0.259$
5. Log $C=0.809+0.324^{a}\log Q_w+0.01148^{a}\,T_a \qquad S_e=0.273$
6. Log $C=1.973+0.00815^{a}\,T_a \qquad S_e=0.312$

III

1. Log $C=+0.963-0.0045\,M_t+0.00852^{a}\,T_a+0.175^{e}\log Q_b+0.188\,P_i+0.452^{a}\log 10\,R_q \qquad S_e=0.297$
2. Log $C=+0.930+0.00845^{a}\,T_a+0.183^{e}\log Q_b+0.196\,P_i+0.453^{a}\log 10\,R_q \qquad \mathrm{S}_e=0.295$
3. Log $C=+1.236+0.00893^{a}\,T_a+0.114\log Q_b+0.404^{a}\log 10\,R_q \qquad S_e=0.295$
4. Log $C=1.576+0.00800^{a}\,T_a+0.368^{b}\log 10\,R_q \qquad S_e=0.296$
5. Log $C=1.973+0.00815^{a}\,T_a \qquad S_e=0.314$

IV

1. Log $C=0.586+0.397^{a}\log Q_w-0.00242\,M_t+0.01101^{a}\,T_a-0.040\log Q_b+0.278^{e}\,P_i \qquad S_e=0.270$
2. Log $C=0.470+0.396^{a}\log Q_w-0.00199\,M_t+0.01104^{a}\,T_a+0.311^{d}\,P_i \qquad S_e=0.268$
3. Log $C=0.462+0.391^{a}\log Q_w+0.01057^{a}\,T_a+0.304^{d}\,P_i \qquad S_e=0.268$
4. Log $C=0.809+0.324^{a}\log Q_w+0.01148^{a}\,T_a \qquad S_e=0.273$
5. Log $C=1.973+0.00815^{a}\,T_a \qquad S_e=0.312$

V

1. Log $\mathrm{C}=+0.791-0.098\log Q_w-0.00200\,M_t+0.01083^{a}\,T_a-0.0214\log Q_b+0.509^{d}\log P_n \qquad S_e=0.269$
2. Log $C=+0.745-0.125\log Q_w-0.00176\,M_t+0.01085^{a}\,T_a+0.535^{c}\log P_n \qquad S_e=0.267$
3. Log $C=0.719-0.00178\,M_t+0.01125^{a}\,T_a+0.402^{a}\log P_n \qquad S_e=0.266$
4. Log $C=0.704+0.01082^{a}\,T_a+0.399^{a}\log P_n \qquad S_e=0.265$
5. Log $C=+1.563+0.308^{a}\log P_n \qquad S_e=0.311$

VI

1. Log $C=+0.645+0.303^{a}\log Q_w-0.00175\,M_t+0.00902^{a}\,T_a-0.034\log Q_b+0.419^{b}\log 100\,R_t \qquad S_e=0.262$
2. Log $C=+0.568+0.294^{a}\log Q_w-0.00136\,M_t+0.00901^{a}\,T_a+0.436^{b}\log 100\,R_t \qquad S_e=0.260$
3. Log $C=+0.554+0.291^{a}\log Q_w+0.00864^{a}\,T_a+0.441^{b}\log 100\,R_i \qquad S_e=0.259$
4. Log $C=0.809+0.324^{a}\log Q_w+0.01148^{a}\,T_a \qquad S_e=0.273$
5. Log $C=1.973+0.00815^{a}\,T_a \qquad S_e=0.312$

VII

1. Log $Q_s=-1.456+1.363^{a}\log Q_w-0.00313\,M_t+0.01030^{a}\,T_a-0.151\log Q_b+0.141\,P_i-0.016\log 10\,R_q \qquad S_e=0.282$
2. Log $Q_s=-1.464+1.355^{a}\log Q_w-0.00308\,M_t+0.01025^{a}\,T_a-0.144^{e}\log Q_b+0.143\,P_t \qquad S_e=0.280$
3. Log $Q_s=-1.220+1.333^{a}\log Q_w-0.00345^{e}\,M_t+0.01052^{a}\,T_a-0.186^{d}\log Q_b \qquad S_e=0.279$
4. Log $Q_s=-1.347+1.316^{a}\log Q_w+0.00998^{a}\,T_a-0.133_{e}\log Q_b \qquad S_e=0.280$
5. Log $Q_s=-1.597+1.288^{a}\log Q_w+0.01078^{a}\,T_a \qquad S_e=0.283$
6. Log $Q_s=-0.677+1.182^{a}\log Q_w \qquad S_e=0.324$

VIII

1. Log $Q_s=-1.644+1.406^{a}\log Q_w-0.00254\,M_t+0.00837^{a}\,T_a-0.184^{e}\log Q_b-0.252\log 10\,R_q+0.493^{b}\log 100\,R_t \qquad S_e=0.265$
2. Log $Q_s=-1.761+1.375^{a}\log Q_w+0.00778^{b}\,T_a-0.130\log Q_b-0.221\log 10\,\mathrm{R}_q+0.514^{b}\log 100\,R_i \qquad S_e=0.265$
3. Log $Q_s=-1.739+1.267^{a}\log Q_w+0.00752^{b}\,T_a-0.062\log Q_b+0.449^{b}\log 100\,R_i \qquad S_e=0.265$
4. Log $Q_s=-1.873+1.252^{a}\log Q_w+0.00770^{b}\,T_a+0.478^{b}\log 100\,R_i \qquad S_e=0.265$
5. Log $Q_s=-1.597+1.288^{a}\log Q_w+0.01078^{a}\,T_a \qquad S^{e}=0.283$
6. Log $Q_s=-0.677+1.182^{a}\log Q_w \qquad S_e=0.324$

IX

1. Log $Q_s=-0.584+0.00390\,M_t+0.00166\,T_a+0.654^{b}\log Q_b-0.059\,P_i+1.713^{a}\log 10\,R_q \qquad S_e=0.450$
2. Log $Q_s=-0.686+0.00409\,M_t+0.00149\,T_a+0.678^{a}\log Q_b+1.727^{a}\log 10\,R_q \qquad S_e=0.447$
3. Log $Q_s=-0.571+0.00434\,M_t+0.662^{a}\log Q_b+1.723\log 10\,R_q \qquad S_e=0.444$
4. Log $Q_s=-0.317+0.597^{a}\log Q_b+1.726^{a}\log 10\,R_q \qquad S_e=0.445$
5. Log $Q_s=+1.198+1.537^{a}\log R_q \qquad S_e=0.501$

X

1. $\text{Log } Q_s=-1.464+1.355^{a}\log Q_w-0.00308\,M_t+0.01025^{a}\,T_a-0.144^{e}\log Q_b+0.143\,P_i$ $S_e=0.280$
2. $\text{Log } Q_s=-1.220+1.333^{a}\log Q_w-0.00345^{e}\,M_t+0.01052^{a}\,T_a-0.186^{d}\log Q_b$ $S_e=0.279$
3. $\text{Log } Q_s=-1.347+1.316^{a}\log Q_w+0.00998^{a}\,T_a-0.133^{e}\log Q_b$ $S_e=0.280$
4. $\text{Log } Q_s=-1.597+1.288^{a}\log Q_w+0.01078^{a}\,T_a$ $S_e=0.283$
5. $\text{Log } Q_s=-0.677+1.182^{a}\log Q_w$ $S_e=0.324$

XI

1. $\text{Log } Q_s=-1.401+1.029^{a}\log Q_w-0.00269\,M_t+0.01005^{a}\,T_a-0.119\log Q_b+0.431\log P_n$ $S_e=0.278$
2. $\text{Log } Q_s=-1.528+0.961^{a}\log Q_w+0.00957^{a}\,T_a-0.067\log Q_b+0.403^{e}\log P_n$ $S_e=0.278$
3. $\text{Log } Q_s=-1.668+0.878^{a}\log Q_w+0.00981^{a}\,T_a+0.485^{c}\log P_n$ $S_e=0.277$
4. $\text{Log } Q_s=-1.597+1.288^{a}\log Q_w+0.01078^{a}\,T_a$ $S_e=0.283$
5. $\text{Log } Q_s=-0.677+1.182^{a}\log Q_w$ $S_e=0.324$

XII

1. $\text{Log } Q_s=-1.642+1.280^{a}\log Q_w-0.00205M_t+0.00797^{b}T_a-0.098\log Q_b+0.425^{b}\log 100\,R_i$ $S_e=0.266$
2. $\text{Log } Q=-1.739+1.267^{a}\log Q_w+0.00752^{b}T_a-0.062\log Q_b+0.449^{b}\log 100\,R_i$ $S_e=0.265$
3. $\text{Log } Q=-1.873+1.252^{a}\log Q_w+0.00770^{b}T_a+0.478^{b}\log 100\,\mathrm{R}_i$ $S_e=0.265$
4. $\text{Log } Q=-1.597+1.288^{a}\log Q_w+0.01078^{a}T_a$ $S_e=0.283$
5. $\text{Log } Q=-0.677+1.182^{a}\log Q_w$ $\mathrm{S}_e=0.324$

RAPPAHANNOCK RIVER AT REMINGTON, VA.

Surface runoff—82 storm events

I

1. $\text{Log } C=1.328+0.323^{c}\log Q_w-0.00276^{e}M_t+0.00925^{a}T_a-0.092\log Q_b+0.154P_i-0.171\log 10R_q$ $S_e=0.247$
2. $\text{Log } C=1.130+0.270^{b}\log Q_w-0.00202M_t+0.00890^{a}T_a+0.207^{e}P_i-0.0752\log 10R_q$ $S_e=0.246$
3. $\text{Log } C=1.202+0.235^{a}\log Q_w-0.00215_{e}M_t+0.00850^{a}T_a+0.190^{e}P_i$ $S_e=0.245$
4. $\text{Log } C=1.462+0.191^{b}\log Q_w-0.00229^{e}M_t+0.00892^{a}T_a$ $S_e=0.246$
5. $\text{Log } C=1.448+0.184^{b}\log Q_w+0.00843^{a}T_a$ $S_e=0.248$
6. $\text{Log } C=2.162+0.00671^{a}T_a$ $S_e=0.263$

II

1. $\text{Log } C=1.395+0.325^{b}\log Q_w-0.00278^{e}M_t+0.00804^{a}T_a-0.117\log Q_b-0.257\log 10R_q+0.221^{d}\log 100R_i$ $S_e=0.245$
2. $\text{Log } C=1.230+0.238^{b}\log Q_w-0.00189M_t+0.00753^{a}T_a-0.126\log 10R_q+0.240^{d}\log 100R_i$ $S_e=0.245$
3. $\text{Log } C=1.333+0.187^{b}\log Q_w-0.00211^{e}M_t+0.00711^{b}T_a+0.204^{d}\log 100R_i$ $S_e=0.244$
4. $\text{Log } C=1.313+0.180^{b}\log Q_w+0.00656^{b}T_a+0.215^{d}\log 100R_i$ $S_e=0.246$
5. $\text{Log } C=1.448+0.184^{b}\log Q_w+0.00843^{a}\,T_a$ $S_e=0.248$
6. $\text{Log } C=2.162+0.00671^{a}T_a$ $S_e=0.263$

Surface runoff—124 storm events

[Rainfall data not available]

III

1. $\text{Log } C=0.826+0.286^{a}\log Q_w-0.00182^{b}\,M_t+0.00791^{a}\,T_a+0.0734\log Q_b+0.252^{d}\,P_i$ $S_e=0.239$
2. $\text{Log } C=1.059+0.289^{a}\log Q_w-0.00190^{c}\,M_t+0.00760^{a}\,T_a+0.199^{e}\,P_i$ $S_e=0.239$
3. $\text{Log } C=1.373+0.232^{a}\log Q_w-0.00208^{b}\,M_t+0.00792^{a}\,T_a$ $S_e=0.240$
4. $\text{Log } C+1.280+0.233^{a}\log Q_w+0.00782^{a}\,T_a$ $S_e=0.246$
5. $\text{Log } C=2.193+0.00544^{a}\,T_a$ $S_e=0.267$

1

RAPIDAN RIVER NEAR CULPEPER, VA.

Surface runoff—85 storm events

1. $\text{Log } C=0.768+0.529^{a}\log Q_w-0.00284^{e}\,M_t+0.00958^{a}\,T_a-0.121\log Q_b+0.395^{d}\,P_i-0.300^{e}\log 10\,R_q$ $S_e=0.280$
2. $\text{Log } C=0.456+0.489^{a}\log Q_w-0.00209\,M_t+0.00962^{a}\,T_a+0.421^{c}\,P_i-0.208\log 10\,R_q$ $S_e=0.280$
3. $\text{Log } C=0.355+0.524^{a}\log Q_w+0.00970^{a}\,T_a+0.429^{c}\,P_i-0.275^{d}\log 10\,R_q$ $S_e=0.281$
4. $\text{Log } C=0.566+0.400^{a}\log Q_w+0.00820^{a}\,T_a+0.354^{d}P_i$ $S_e=0.284$
5. $\text{Log } C=0.957+0.335^{d}\log Q_w+0.00904^{a}\,T_a$ $S_e=0.287$
6. $\text{Log } C=1.702+0.259^{a}\log Q_w$ $S_e=0.315$

II

1. $\text{Log } C=1.141+0.449^{a}\log Q_w-0.00268\,M_t+0.00947^{a}\,T_a-0.126\log Q_b-0.283^{e}\log 10\,R_q \qquad S_e=0.287$
2. $\text{Log } C=1.307+0.438^{a}\log Q_w-0.00313^{e}\,M_t+0.01008^{a}\,T_a-0.149\log Q_b-0.249\log 10\,R_q \qquad S_e=0.286$
3. $\text{Log } C=0.960+0.380^{a}\log Q_w-0.00222\,M_t+0.01017^{a}\,T_a-0.130\log 10\,R_q \qquad S_e=0.287$
4. $\text{Log } C=1.035+0.327^{a}\log Q_w-0.00268^{e}\,M_t+0.00944^{a}\,T_a \qquad S_e=0.286$
5. $\text{Log } C=0.9568+0.335^{a}\log Q_w+0.00904^{a}\,T_a \qquad S_e=0.287$
6. $\text{Log } C=1.702+0.259^{a}\log Q_a \qquad S_e=0.315$

JAMES RIVER AT BUCHANAN, VA.

Surface runoff—65 storm events

[Computer option to discard least significant variable or each combination was not used]

I

$\text{Log C}=+0.960+0.532^{b}\log Q_w-0.00530^{b}M_t+0.00777^{b}\,T_a-0.556^{a}\log Q_b+1.019^{a}\,P_t \qquad S_e=0.230$

II

$\text{Log C}=+1.783-0.486^{d}\log Q_w-0.00521^{b}\,M_t+0.00807^{b}\,T_a-0.572^{a}\log Q_b+1.027^{a}\log P_n \qquad S_e=0.229$

III

$\text{Log C}=+1.625+0.418^{a}\log Q_w-0.00633^{b}\,M_t+0.00826^{c}\,T_a-0.482^{a}\log Q_b \qquad S_e=0.252$

IV

$\text{Log C}=-0.649+0.454^{a}\log Q_w-0.00333^{d}\,M_t+0.01175^{a}\,T_a+0.769^{c}\,P_t \qquad \text{S}_e=0.269$

V

$\text{Log C}=+0.0359+0.373^{a}\log Q_w-0.00434^{c}M_t+0.01170^{a}\,T_a \qquad S_e=0.278$

VI

$\text{Log C}=+1.352+0.203^{b}\log Q_w-0.00380^{d}\,M_t \qquad S_e=0.308$

JAMES RIVER AT SCOTTSVILLE, VA.

Surface runoff—67 storm events

I

1. $\text{Log } C=+0.832-0.359^{e}\log Q_w-0.00321^{c}M_t+0.00290^{e}T_a-0.184^{d}\log Q_b+0.926^{a}\log P_n \qquad S_e=0.186$
2. $\text{Log } C=1.245-0.446^{c}\log Q_w-0.00333^{c}M_t-0.217^{c}\log Q_b+0.989^{a}\log P_n \qquad S_e=0.188$
3. $\text{Log } C=1.271-0.00293^{c}M_t-0.262^{b}\log Q_b+0.525^{a}\log P_n \qquad S_e=0.192$
4. $\text{Log } C=1.129-0.211^{c}\log Q_b+0.496^{a}\log P_n \qquad S_e=0.198$
5. $\text{Log } C=0.683+0.425^{a}\log P_n \qquad S_e=0.204$

II

1. $\text{Log } C=0.211+0.560^{a}\log Q_w-0.00297^{c}\,M_t+0.00286^{e}\,T_a-0.196^{c}\log Q_b+0.770^{b}\,P_t \qquad S_e=0.194$
2. $\text{Log } C=0.554+0.537^{a}\log Q_w-0.00309^{c}M_t-0.229^{c}\log Q_b+0.846^{a}\,P_t \qquad S_e=0.196$
3. $\text{Log } C=0.489+0.504^{a}\log Q_w-0.182^{d}\log Q_b+0.751^{b}\,P_t \qquad S_e=0.202$
4. $\text{Log } C=+0.074+0.451^{a}\log Q_w+0.808^{b}\,P_t \qquad S_e=0.206$
5. $\text{Log } C=+0.806+0.357^{a}\log Q_w \qquad S_e=0.221$

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