MAGNITUDE AND FREQUENCY OF FORCES IN GEOMORPHIC PROCESSES[1]

M. GORDON WOLMAN AND JOHN P. MILLER
Johns Hopkins University and Harvard University

ABSTRACT

The relative importance in geomorphic processes of extreme or catastrophic events and more frequent events of smaller magnitude can be measured in terms of (1) the relative amounts of "work" done on the landscape and (2) in terms of the formation of specific features of the landscape.

For many processes, above the level of competence, the rate of movement of material can be expressed as a power function of some stress, as for example, shear stress. Because the frequency distributions of the magnitudes of many natural events, such as floods, rainfall, and wind speeds, approximate log-normal distributions, the product of frequency and rate, a measure of the work performed by events having different frequencies and magnitudes will attain a maximum. The frequency at which this maximum occurs provides a measure of the level at which the largest portion of the total work is accomplished. Analysis of records of sediment transported by rivers indicates that the largest portion of the total load is carried by flows which occur on the average once or twice each year. As the variability of the flow increases and hence as the size of the drainage basin decreases, a larger percentage of the total load is carried by less frequent flows. In many basins 90 per cent of the sediment is removed by storm discharges which recur at least once every five years.

Transport of sand and dust by wind in general follows the same laws. The extreme velocities associated with infrequent events are compensated for by their rarity, and it is found that the greatest bulk of sediment is transported by more moderate events.

Many rivers are competent to erode both bed and banks during moderate flows. Observations of natural channels suggest that the channel shape as well as the dimensions of meandering rivers appear to be associated with flows at or near the bankfull stage. The fact that the bankfull stage recurs on the average once every year or two years indicates that these features of many alluvial rivers are controlled by these more frequent flows rather than by the rarer events of catastrophic magnitude. Because the equilibrium form of wind-blown dunes and of wave-formed beaches is quite unstable, the frequency of the events responsible for their form is less clearly definable. However, dune form and orientation are determined by both wind velocity and frequency. Similarly, a hypothetical example suggests that beach slope oscillates about a mean value related in part to wave characteristics generated by winds of moderate speed.

Where stresses generated by frequent events are incompetent to transport available materials, less frequent ones of greater magnitude are obviously required. Closer observation of many geomorphic processes is required before the relative importance of different processes and of events of differing magnitude and frequency in the formation of given features of the landscape can be adequately evaluated.

INTRODUCTION

Denudation of the earth's surface and modification of existing land forms involve forces which are ultimately controlled by highly variable atmospheric influences coupled with the unvarying effects of gravity. Almost any specific mechanism requires that a certain threshold value of force be exceeded. However, above this threshold or critical limit there occurs a wide range in magnitude of forces which results from variations in intensity of precipitation, wind speed, etc. The problem to be examined in this paper is the relative importance of extremes or catastrophic events and more ordinary events with regard to their geomorphic effectiveness expressed in terms of material moved and modification of surface form. Thus this is a re-examination of the concept of "effective force" in landscape development.

It is widely believed that the infrequent events of immense magnitude are most effective in the progressive denudation of the earth's surface. Although this belief might seem to be supported by observations of some individual events, such as large floods, tsunamis, and dust storms, the catastrophic event is not necessarily the critical factor responsible for the development of land forms. Available evidence indicates that evaluation of the effectiveness of a specific mechanism and of the relative importance of different geomorphic processes in mold-

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ing specific forms involves the frequency of occurrence as well as the magnitude of individual events.

Evidence related to the influence of frequent events of small magnitude is far less spectacular than the exciting descriptions of the Johnstown flood or the Galveston disaster. It may also be true that in many instances the importance of the latter actually is directly proportional to their grandeur. The purpose of this paper is not to play down any valid significance of the awesome catastrophes but to demonstrate by means of several examples that a more accurate picture of the over-all effectiveness of various geomorphic processes should include not only the rare extreme events but also events of moderate intensity which recur much more frequently.

The relative amount of "work" done during different events is not necessarily synonymous with the relative importance of these events in forming a landscape or a particular feature of the landscape. The effectiveness of an event of a given frequency in terms of its performance of work is measurable both by its magnitude and by the frequency with which it recurs. Thus the relative amounts of work performed by events such as floods of different magnitude and frequency are measurable in part, at least, by comparisons of the relative quantities of sediment transported. On the other hand, although related to the form of the landscape, the ranking of events in terms of the relative amounts of work performed is not necessarily directly correlated with their relative importance in the determination of river pattern, drainage density, slope form, or other aspects of the landscape. This paper deals first with the significance of frequency and magnitude in terms of "work done" and second in terms of the formation of specific features of the landscape.

Any discussion of the frequency of events of geomorphic significance clearly raises some concern about the length of the available record. On the geologic time scale any record of water and sediment discharge is infinitesimally short. On the other hand, where something is known about mechanical aspects of the process, a record of twenty-five to fifty years, considerably longer than most river records, may be sufficient to provide an adequate sample of a river's regimen of flow for certain kinds of analyses. The significance of the likely omission of some extremely high as well as extremely low values will vary with the measure of effective force used. Thus for the case of effective force measured in terms of competence, a "rare" event not experienced in historic time may have recurred a significant number of times in the geologic record. However, because of their relative rarity, such events are of less significance in analyses concerned with percentages of material moved by events of varying frequency and magnitude.

EROSION AND SEDIMENT TRANSPORT

GENERAL CASE

The movement of sediment by water or air is essentially dependent upon shear stress and, according to Malina (1941), Bagnold (1941), Brown (1954), etc., can be described by the equation

$$q = k(\tau - \tau_c)^n , \qquad (1)$$

where q is the rate of transport, k is a constant related to the characteristics of the material transported, τ is the shear stress per unit area, and τ_c is a critical or threshold shear stress required to move the material. In its simplest form, equation (1) is essentially a power function

$$q = x^n , \qquad (2)$$

where q is the rate of movement, and x is a variable, some responsible stress such as shear, etc., which exceeds the required threshold value. This relation is shown diagrammatically in figure 1, *a*.

The distribution in time of many hydrologic and meteorologic events, such as wind speeds or flood peaks, has been shown to approximate a log-normal distribution (see Chow, 1954, and Krumbein, 1955, for numerous examples). These events may be visualized as cumulative applied stresses acting upon particular segments of the landscape. If the stress is log-normally distributed and continuous (fig. 1, *b*) and if the quantity or rate of movement is related to some power of this stress, then the relation between stress and the product of frequency times rate of movement must attain a maximum. The recurrence interval or frequency at which this maximum occurs is controlled by the relative rates of change of q with the

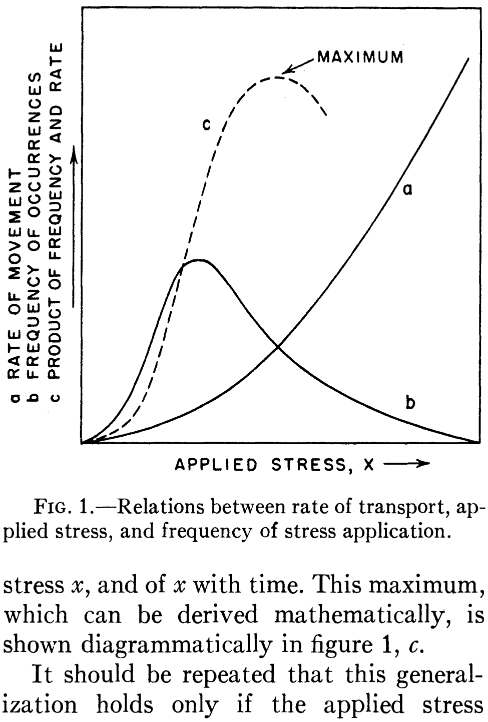

FIG. 1.—Relations between rate of transport, applied stress, and frequency of stress application.

stress x, and of x with time. This maximum, which can be derived mathematically, is shown diagrammatically in figure 1, *c*.

It should be repeated that this generalization holds only if the applied stress exceeds a threshold value. Below this value no work is done in moving material. This means, of course, that both the equation of transport and the frequency distribution must apply to all values of the applied stress above this threshold value. These conditions are met in several of the simple examples that follow. In these, the recurrence interval at which the product of frequency and rate of movement is a maximum (fig. 1, *c*) and the cumulative percentage of the total work performed by successively larger events provide an indirect measure of the relative amounts of work performed by events of different magnitude and frequency.

TRANSPORT OF SEDIMENT BY RIVERS

Most rivers in flood carry large amounts of sediment. The relative importance of different flows can be evaluated by comparing the quantity of sediment transported by great, rare floods with the quantity carried by more frequent, lesser flows. If the quantities of material carried by flows of various magnitudes are known and the frequency of occurrence of each flow is also known, the per cent of the total transported by each flow can be computed from the equation shown at the bottom of this page. Cumulating these percentages gives the proportion of the total carried by successively higher flows.

The computation has been made for the Rio Puerco in the western United States and for Brandywine Creek in the eastern United States. The results of the analysis are given in table 1. Because the results vary depending upon the type of distribution used, two analyses are given for each stream. The use of volumes of runoff in individual peaks eliminates a large number of days of steady base flow in each of which varying amounts of sediment are transported. The results in this case exaggerate the effect of higher flows. Although the record of peaks includes higher flows, the results are of less general value because, unlike the duration curve which is a continuous record, the individual peaks are discrete and do not form a continuous sequence.

Despite climatic and physiographic differences, 50 per cent of the total suspended load of both streams was transported by

$$\frac{\text{(Sediment carried by given flow) (Frequency of given flow)}}{\text{Total sediment transported}}\,100$$

$$= \text{Per cent of total sediment carried by flows of different magnitude}\,.$$

flows which occur on the average one day or more per year (table 1, col. 4). Although many fewer flows were required to transport the remaining 50 per cent of the sediment, the data indicate that at least half the suspended sediment is removed from these drainage basins by low and moderate flows.

Catastrophic floods are those which are truly rare. Arbitrarily we might say that they recur, on the average, once in fifty or a hundred years. Although less satisfactory than the data based on the continuous daily record of flow duration, the data in table 1 show that 90 per cent of the sediment in both these basins (col. 6) is transported by storm runoffs or discharges which recur at least once every five years. The relative proportions of load carried by flows of various magnitudes differ considerably in different rivers. However, for these examples, from both a humid and a semiarid region, by far the greatest part of the total sediment removed from the drainage basins during the period of record was carried by small to moderate flows and not by catastrophic floods. Although the extremely large floods carry greater quantities of sediment, they occur so rarely that from the standpoint of transport their over-all effectiveness is less than that of the smaller and more frequent floods.

In each example the measured load probably represents a large percentage of the total sediment leaving the basin. On Brandywine Creek little of the very coarse sediment not included in the samples appears to leave the basin, whereas on the Rio Puerco most of the sediment is fine material, and the measured load is probably representative of the total load.

It must be emphasized that this analysis of the transport of suspended sediment does not give a picture of the effect of the removal of this material on the physiography of the basin. It does, however, provide some measure of the relative amounts of work done by large and small flows. Their impact upon the form of the landscape is considered more specifically elsewhere in this paper.

Another way of investigating frequency relations of sediment transport is to consider load directly, apart from the water discharge. This is appropriate because maximum sediment loads generally do not coincide with peak flood discharges. Snow-fed rivers commonly carry their maximum discharges during the spring melt season and their largest sediment loads during heavy rains of summer and fall. Four streams, all of them in the West, were considered by this method. The Colorado River at Grand Canyon has a large drainage basin, derives the major part of its flow from snowmelt,

TABLE 1

PERCENTAGE OF SUSPENDED SEDIMENT TRANSPORTED BY FLOWS OF DIFFERENT MAGNITUDES*

(1)	Distribution Measure of Flow Used in Analysis (2)	Magnitude of Flow below Which 50 Per Cent of Total Sediment Is Transported (3)	Frequency of Occurrence of Flow in Col. 3 (4)	Magnitude of Flow below Which 90 Per Cent of Total Sediment Is Transported (5)	Frequency of Occurrence of Flow in Col. 5 (Per Year) (6)	Remarks (7)
Rio Puerco at Rio Puerco, N.M......	Volume of flow, individual rises	1,800 cfs-days	2 times/yr	9,500 cfs-days	0.26 times	
Rio Puerco near Bernardo, N.M.......	Daily discharge, duration curve	950 cfs	Equaled or exceeded 6 days/yr	3,400 cfs	0.7 days	Zero flow approximately 70 per cent of year
Brandywine Creek at Wilmington, Del...	Volume of flow, individual rises	9,000 cfs-days	0.3 per year	11,000 cfs-days	0.2 times	
Brandywine Creek at Wilmington, Del...	Daily discharge, duration curve	1,900 cfs	Equaled or exceeded 11 days/yr	8,200 cfs	0.2 days	

* Flow data are from *Water Supply Papers*, published annually by the U.S. Geological Survey, entitled "Surface Water Supply of the United States." Sediment data are from reports entitled "Quality of Surface Waters of the United States."

and drains a variety of rock types which range widely in sediment-yielding potential. The Rio Puerco is an ephemeral stream which carries tremendous sediment loads, derived mostly from unconsolidated deposits and soft shale bedrock, during intense summer and fall rains. The Cheyenne River is a plains stream which drains poorly consolidated rocks and unconsolidated sediments. It shows wide variations in flow and experiences floods which result from summer rains. The Niobrara River is characterized by relatively uniform flow and load, which result from the regulating effects of groundwater storage in the Sand Hills.

recur more frequently than once in 10 years. A larger percentage of the total transport occurs during infrequent floods for the streams which have highly variable flow. Events which recur more than once per year account for 78–95 per cent of the total suspended load. Transport of half the average annual load takes only a few days for Rio Puerco and the Cheyenne River, about a month for the Colorado, and three months for the Niobrara.

It should be emphasized that the data referred to in figure 2 are for suspended load only. Except for the Niobrara, suspended load probably accounts for 90 per cent of the total clastic load. Colby and Hembree (1957) have estimated that suspended load of the Niobrara near Cody amounts to roughly half the total sediment discharge.

TABLE 2

TIME REQUIRED TO TRANSPORT VARIOUS PERCENTAGES OF TOTAL SUSPENDED LOAD*

		Percentage of Total Suspended Load Carried during			
River and Station	Drainage Area (Sq. Miles)	Max. Day	10 Max. Days	Events Which Recur 1 Day/Yr	Days/Yr Required To Transport 50 Per Cent of Load
Colorado River at Grand Canyon, Ariz.	137,800	0.5	4	92	31
Rio Puerco at Rio Puerco, N.M.	5,160	5	31	82	4
Cheyenne River near Hot Springs, S.D.	8,710	5	28	78	4
Niobrara River near Cody, Neb.	....	2	7	95	95

* Flow data are from *Water Supply Papers*, published annually by the U.S. Geological Survey, entitled "Surface Water Supply of the United States." Sediment data are from reports entitled "Quality of Surface Waters of the United States."

For each stream, daily suspended loads during the period of record were arranged in order of magnitude from largest to smallest, and the percentages of total load and total time were computed. For example, the largest daily load carried by the Colorado was 15.8×10^6 tons. This corresponds to 0.5 per cent of the total load ($3{,}062 \times 10^6$ tons) carried during 0.012 per cent of the total time (3,036 days). Both percentages of load and time were cumulated and the results, partially summarized in table 2, are plotted in figure 2. Because only the larger loads were considered, the curves in some cases do not account for much more than half the total time involved.

For all four streams, 98–99 per cent of the total load is carried during events which

The curves in figure 2 also suggest that the greater the variability of the runoff, the larger the percentage of the total load which is likely to be carried by infrequent flows. Because runoff becomes increasingly variable as drainage area is reduced, it is to be expected that the smaller the drainage area, the larger will be the percentage of sediment carried by the less frequent flows. Thus Culler (personal communication) has shown that for the Cheyenne River near Hot Springs, South Dakota (drainage area 8,700 square miles), 42 per cent of the average annual runoff is produced by storms having a frequency of once each year. In contrast, storms of similar frequency account for 78 per cent of the average annual runoff from drainage areas ranging in size from 0.1 to 3 square miles in the same region. This fact, combined with the higher discharge per square mile produced over small areas, would produce not only high-sediment discharges per square mile but would also increase the percentage of sediment carried by the less frequent events.

Southern California provides a similar example of the influence of size of drainage area on the frequency characteristics of sediment transport. The extreme quantities of sediment produced by small watersheds heading in the mountains near Los Angeles have been discussed by many authors. Because much of the sediment is coarse debris and difficult to measure, the data on magnitude and frequency of transport are imperfect. A recent report by Ferrell *et al.* (1957) provides some new data and also presents a comprehensive review of efforts to apply all available information to planning control measures. All the 192 basins considered are less than 8 square miles in area. Using a 50-year synthetic rainfall record,[2] it is concluded that 87–91 per cent of the debris is moved by runoff from storms of recurrence interval >5 years and half of the debris by floods of recurrence interval >21–28 years. Considering only the basins for which there are records extending over 20 years yields somewhat different conclusions, however, as is shown by table 3.

[2] Based on precipitation data for stations with the area considered.

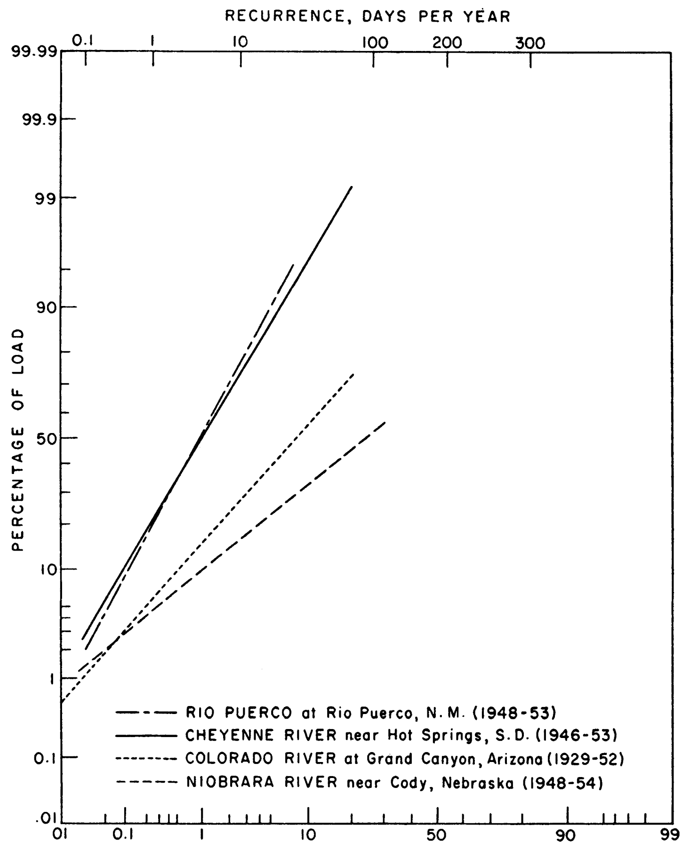

FIG. 2.—Plot of cumulative per cent of time against cumulative percentage of total suspended load

The maximum flood of one-day duration accounted for 29 per cent of the total debris moved during the period of twenty years, as compared with 4 per cent predicted from theoretical considerations. Thus even under these extreme conditions of slope and precipitation the available record indicates that more than 50 per cent of the load is carried by flows which recur once every two or three years.

TABLE 3

MOVEMENT OF SEDIMENT IN MOUNTAINOUS WATERSHEDS NEAR LOS ANGELES

Recurrence Interval (Yr.)	Percentage Total Debris Moved by Floods of Recurrence Interval Equal to or Less than Given Value	
	Actual*	Theoretical†
1	39	5
2	56	14
5	59	33

* 13 of 20 years were drought years.
† 50-year synthetic record.

TABLE 4

SUSPENDED LOAD TRANSPORTED FROM SMALL DRAINAGE BASINS*

Location	Basin Area (Sq. Miles)	Maximum Daily Load (Per Cent Total for Period)
Kansas	15– 52	23–29
Missouri	95–200	7–22
North Carolina	11–124	7–18
South Carolina	106–351	4– 8
Oklahoma	13–165	15–53
Texas	30–166	14–29
Washington	7–132	10–22
Wisconsin	77–119	15–36
Pennsylvania	10– 15	2–39

* Data for Pennsylvania are from Culbertson (1957); all other data are from Love (1936).

It might be supposed that the regimen of sediment transport in regions of perennial stream flow is somewhat less sensitive to differences in drainage area. Data for the Yadkin River basin in North Carolina (drainage area 2,280 square miles) indicate that 90 per cent of the total sediment is transported by flows which occur, on the average, three or more days per year. Flows of similar frequency on the smaller Brandywine Creek in eastern Pennsylvania (drainage area 312 square miles) transport only 54 per cent of the total load. For very small drainage basins, differences between humid and arid regions appear to be slight.

Data given by Love (1936) and Culbertson (1957) indicate that a larger fraction of the total load transported from small basins is carried by infrequent flows (see table 4). Suspended sediment was measured by Love during a fifteen-month period at stations in 36 basins which represent a wide range of climatic and physiographic conditions. A single day (0.2 per cent of time) accounted for 4–53 per cent of the total for the period, and in three-fourths of the basins more than 10 per cent of the total was carried in one day. Some of the streams in Missouri and Wisconsin transported 90 per cent of the total load in 10–12 days (2 per cent of the time.) Culbertson's data refer to a single year of record.

In relating sediment transportation to frequency of runoff, it is interesting to note that Smith and Wischmeier (1957) have shown that the kinetic energy of rainfall decreases rapidly with increasing intensity (less frequent events). Because erosion was found to be a function of the product of precipitation intensity and kinetic energy (the time or frequency factor), as in the case of sediment transport, greater frequency compensates in large measure for the lower intensity.

In summary, these comparisons indicate that most of the work of moving sediment from the drainage basin is done by frequent flows of moderate magnitude. As used here, a "frequent" event recurs at least once each year or two and in many cases several or more times per year. The evidence also suggests that the more variable the regimen of flow of the stream, the larger the percentage of total sediment load which is likely to be carried by the infrequent flows. However, even for many small streams a large percentage of the sediment is carried by flows which recur at least once every five years.

RELATIVE AMOUNTS OF DISSOLVED AND SUSPENDED LOAD

The significance of frequent events of slight intensity is perhaps even better illustrated by a consideration of the dissolved load transported by rivers. Although the process of solution may be aided by floods and fast-flowing streams, it is more dependent on the presence of soluble, permeable rocks and abundant precipitation to percolate through them. Comparisons of the percentage of the total solids removed in solution and as suspended load from drainage basins underlain by diverse lithologies provide the general case for this discussion.

The percentage of the material carried in solution is not in itself a measure of the relative importance of frequent, moderate flows as opposed to larger and less frequent ones. However, this percentage should reflect the degree of influence of the lesser flows because (1) unlike the suspended load which increases both in concentration and volume with increasing flow, a large part of the dissolved load is contributed by ground-water flow (Durum, 1953), and thus concentration decreases with increasing flow thereby reducing in terms of volume the relative importance of the higher flows; (2) the frequency distribution of flows is skewed toward the smaller and more frequent flows. The high concentration experienced during low flows is supported by many observations (Durum, 1953). Figure 3 shows, for example, the rate of increase of dissolved load with increasing discharge at several stations on different rivers. As the slope of each curve on the graph is less than one, it is clear that in all cases concentration decreases with increasing discharge. Combining this information with data on the frequency of occurrence of flows of varying magnitude yields a relation similar to those described for the transport of suspended load. The example suggests that a very large part of the "work" done in the transport of dissolved load is by flows comparable to the mean or even the median flow of the stream. It follows, then, that the higher the percentage of the total load which is carried in solution, the greater the relative importance of the frequent smaller flows.

It should be emphasized that acquisition and transport of dissolved load depend only slightly on stream discharge derived from surface runoff. Durum (1953) estimated that 74 per cent of the dissolved load carried annually by the Saline River at Russell, Kansas, is derived from ground water and the remainder from contact of stream water with the channel perimeter and particularly from solution of the clastic load. Ground water accounts for only 35 per cent of the annual water discharge at Russell. If the surface runoff contributes clastic sediment, the dissolved load may be increased and thereby affected by magnitude and frequency of flow. If the stream carries essentially no suspended load, then flow frequency has little bearing on transport of dissolved load. Most ground waters are unsaturated and hence discharges above base flow simply dilute the dissolved load. In any case, the concept of effective force is applicable to transport of dissolved load only indirectly through its bearing on transport of suspended load.

The percentage of the total load which is carried in solution varies with the geologic topographic, and climatic characteristics on the drainage basin. Thus for the Salief, River basin in Kansas (table 5), a relatively large river in the semiarid plains, 13 per cent of the total load is dissolved. The Bighorn River at Thermopolis, Wyoming, which derives part of its flow from the mountains, also carries 13 per cent of its total load in solution. The discharge at Thermoplis contains considerable salt derived from the return flow of irrigation water. Rates of solution in various tributary basins upstream from Thermopolis are highly variable. Although the streams in the headwaters of this basın are dilute, precipitation is great and hence the streams transport a large volume of material in solution—evidence that the basin is undergoing more

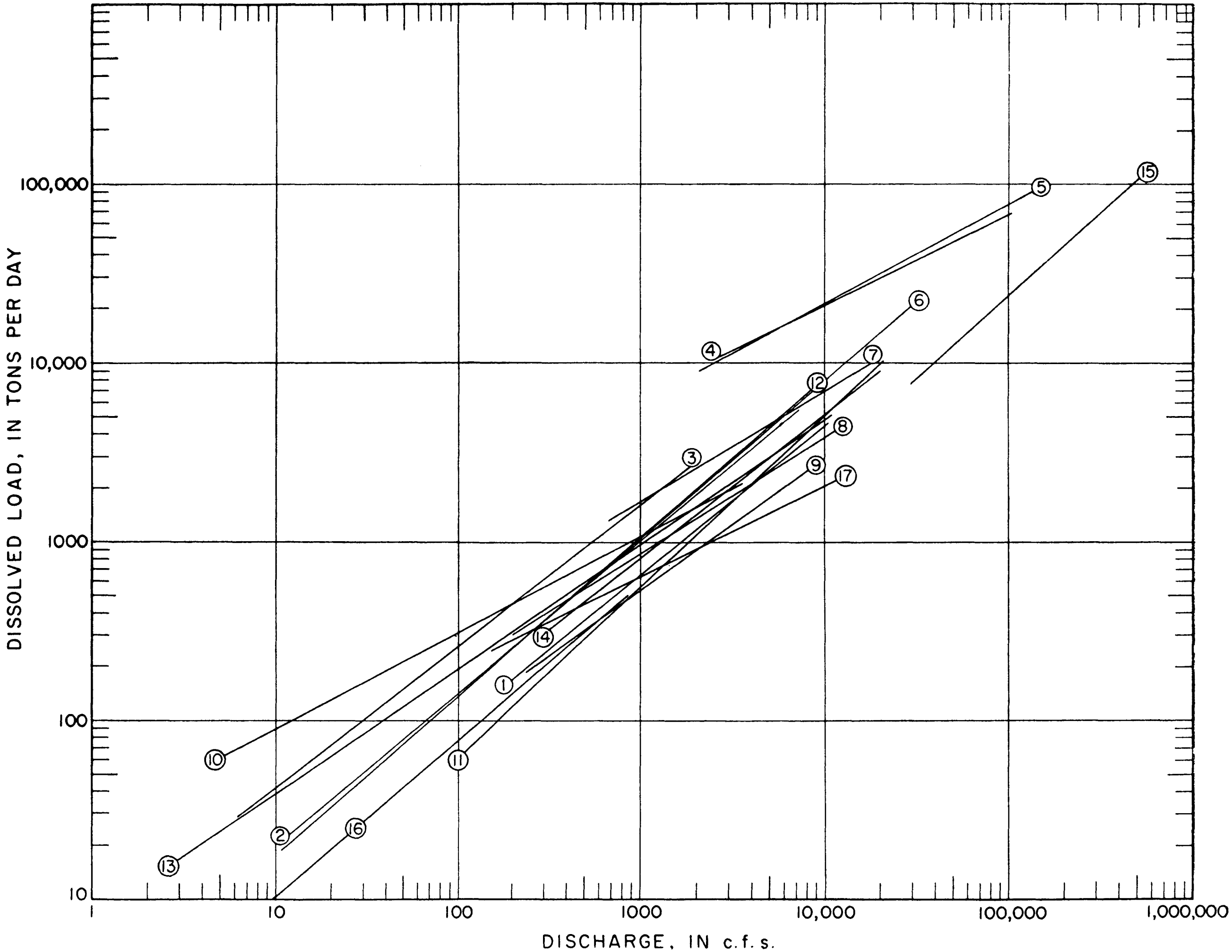

FIG. 3.—Relation of dissolved load to stream discharge at various measuring stations. Key to stations: *1.* Rio Grande at Otowi, N.M.; *2.* Rio Grande at San Acacia, N.M.; *3.* Rio Grande at San Marcial, N.M.; *4.* Colorado River at Lees Ferry, Ariz.; *5.* Colorado River at Grand Canyon, Ariz.; *6.* San Juan River at Bluff, Utah; *7.* Bighorn River at Thermopolis, Wyo.; *8.* Shoshone River at Byron, Wyo.; *9.* Wind River at Riverton, Wyo.; *10.* Saline River at Russell, Kans.; *11.* Iowa River at Iowa City, Iowa; *12.* White River near Kadoka, S.D.; *13.* Moreau River at Bixby, S.D.; *14.* Cedar River at Cedar Rapids, Iowa; *15.* Columbia River at International Boundary; *16.* Ute Creek near Bueyeros, N.M.; *17.* Allegheny River at Red House, N.Y.

rapid chemical denudation (Colby *et al.*, 1956, p. 139). However, from the lower semiarid parts of the basin large amounts of clastic load are derived. Thus, although the salt discharge at Thermopolis is high, it makes up a relatively small percentage of the total load (table 5). In general, the percentage of dissolved load increases with increasing precipitation and vegetative cover (table 5). However, geologic influences, such as erodibility and content of soluble constituents, may overshadow the effects of climate.

In humid regions perennial stream flow released from ground-water storage results in a large percentage of dissolved load because production of clastic sediment is inhibited by vegetation (Langbein and Schumm, 1958). Unfortunately, suitable data for comparing basins of different types and sizes are not available. Contamination of stream waters by wastes from industrial and domestic sources is the most serious obstacle to such comparisons. Also, there are very few stations in humid regions with adequate records of both dissolved and suspended load, and most of these are for rather large drainage areas. Preliminary estimates by Rainwater (personal communication) indicate that on three small watersheds in Pennsylvania more than 40 per cent of the total load is dissolved (table 5).

To the extent that these comparisons of dissolved and clastic load illustrate the relative apportionment of the "work done" by large and small flows in degrading drainage basins, the above comparisons indicate that much of the work is done by low flows of frequent occurrence. When combined with the observations of suspended sediment load alone, it is clear that very large amounts of material are transported from drainage basins in diverse climatic and physiographic environments by frequent events of small magnitude. Insufficient information is presently available with which to compare the relative importance of infrequent and frequent events in different kinds of drainage basins.

TABLE 5

PERCENTAGE OF TOTAL LOAD CARRIED IN SOLUTION FROM SELECTED DRAINAGE BASINS

River and Location	Drainage Area (Sq. Miles)	Approximate Mean Annual Discharge (cfs per (Sq. Miles)	Average Total Load (Tons per Year)	Per Cent Total Load Carried in Solution
Colorado River at Grand Canyon, Ariz.	137,800	0.1	177,000,000	6
Colorado River near Cisco, Utah	24,100	0.3	22,000,000	20
Green River at Green River, Utah	40,600	0.2	25,000,000	10
San Juan River near Bluff, Utah	23,000	0.1	35,000,000	3
Gunnison River near Grand Junction, Colo.	8,020	0.3	341,000	45
Bighorn River at Thermopolis, Wyo.	8,080	0.2	5,750,000	13
Wind River at Riverton, Wyo.	2,320	0.4	703,000	27
Pogo Agie River near Riverton, Wyo.	2,010	0.3	555,000	45
Wind River near Dubois, Wyo.	233	0.8	174,400	13
Saline River at Russell, Kan.	1,502	0.1	645,000	13
Iowa River at Iowa City, Iowa	3,721	0.5	1,720,000	17
Bixler Run, central Pa.*	15	1.0	2,800	59
Corey Creek, central Pa.*	12	0.6	1,260	44
Elk Run, central Pa.*	10	0.7	1,110	37

* Preliminary data, approximate only.

TRANSPORT BY WIND

Thus far the discussion of relative amounts of work done by events of varying magnitude has been based upon measurements of the transport of material by rivers. This is due primarily to the simplicity of the illustration and also to the fact that a large volume of data is available for analysis. In emphasizing the importance of the more frequent but smaller events, it should be noted that, to the extent that the log-normal distribution describes the frequencies of wind velocities or other currents beyond the necessary threshold, the results of the analyses of river data presumably should apply also to other similar phenomena. The analyses of Zingg (1949), Thom (1954), and many others seem to indicate that a log-normal frequency distribution of wind velocities is a general rule.

Bagnold (1941) shows that movement of dune sand at the Kharga Oasis in Egypt is primarily effected by winds of less than sandstorm velocity (in the terms used here, non-catastrophic) but greater than those which occur a large part of the time (table 6). Similar analyses for the transport of dust by wind can also be made. A measure of the generality of this example is indicated by the data in table 7, which show that a critical wind speed of 20 miles per hour is equaled or exceeded from 5 to 25 per cent of the time at several diverse localities.

In summary, these examples of sediment transport by wind supplement the earlier examples already given from alluvial environments. Both suggest that much of "work" upon the landscape is performed by events of moderate magnitude and relatively frequent occurrence. The common assumption that the rare and infrequent events do the significant work seems to require some modification.

MAGNITUDE AND FREQUENCY OF EVENTS RELATED TO THE FORMATION OF SPECIFIC LANDSCAPE FEATURES

The discussion thus far has considered only process, specifically the effectiveness of various events expressed in terms of the relative amounts of material transported. The following sections describe relations of

TABLE 6

MOVEMENT OF DUNE SAND, KHARGA OASIS, EGYPT*

	A Sand Movement on Dunes Only	B Sand Driving across Country and onto Dunes	C Sand Storms
Velocity, meters/sec†	5.8–10	10–13.5	13.5–15.7
Estimated mean wind velocity, V_m, for categories A, B, and C	7.9	11.3	14
Mean velocity less critical velocity required for movement, $V_m - V_c$	3.5	6.9	9.6
Number of hours of north wind less number of hours of south wind, T	2,015	960	132
Sand movement, q, tons per year proportional to $T\,(V_m - V_c)^3$	8.7×10^4	32×10^4	12×10^4

* Data from Bagnold, 1941, p. 215–216, unidirectional wind assumed.

† 1 meter per second = 2.24 miles per hour.

TABLE 7

APPROXIMATE FREQUENCY OF WIND SPEEDS EXCEEDING 20 MILES PER HOUR AT SELECTED LOCALITIES

Location	Source of Information	Approximate Frequency with Which Wind Speed of 20 mph Is Exceeded (Per Cent)	Type of Data
Dodge City, Kan.	Zingg, 1949	10	April av. wind velocity, 73 yrs.
Beersheba, Israel	Rosenan, 1954	5	Data in personal communication, 7 yrs.
Lake Hefner, Okla.	Harbeck, 1952	5	Continuous, 16 mos.
Washington, D.C.	U. S. Weather Bureau, 1945	24	Days of max, 5 min.; speed, 40 yrs.

processes to specific features of the landscape. These processes are ones in which the applied stress is provided by climatically controlled events, such as river discharges, rainstorms, or wind velocities. The frequency distribution of these events normally includes a relatively large number of events of small magnitude and a small number of events of large magnitude. An understanding of the relative importance of these events in molding specific land forms is dependent upon a rather detailed understanding of the mechanisms and processes by which such land forms are developed. Unfortunately, the number of forms which are understood to this degree is exceedingly small. Nevertheless, the available information appears to warrant a preliminary analysis.

DISCHARGES CONTROLLING RIVER CHANNEL SHAPE AND PATTERN

The shape and pattern of a river channel are to some degree adjusted to the discharge of water and sediment load provided by the drainage basin and to the specific size and shape of the materials provided by the geology of the region (Mackin, 1948; Leopold and Maddock, 1953; Wolman, 1955). Because of the range of discharge to which most natural channels are subject, it is logical to assume that the channel shape is affected by a range of flows rather than by a single discharge. Blench (1951, sec. 6.16), for example, refers to a dominant discharge as the "steady discharge that would produce the same result as the actual varying discharge." Melton (1936, p. 601) suggests that in a stream with low-water channel and floodplain the "floods of greatest geological effect should be of two types: those that nearly fill the channel but do not overtop its banks and those that rise to still greater heights and cover the plain." Using several examples, an attempt is made here to illustrate the way in which events of varying magnitude and frequency actually influence alluvial land forms and to define thereby what might be termed a range of physically effective discharges.

In an analysis of factors controlling bank erosion, Wolman (1959) has shown that lateral cutting of the cohesive channel bank of a small stream in Maryland occurs mostly during the winter months, when flows of a size which occurs eight to ten times per year attack previously wetted banks. Although summer thunderstorms in this area usually provide the highest peak discharge, the dry, hard riverbanks of the summer season are less susceptible to erosion. For this reason the lesser and much more frequent flows of midwinter commonly are able to erode as much as one foot from the channel banks at stages well below bankfull. Thus events of moderate magnitude and relatively frequent occurrence control the erosional form of the channel, including its size and shape. Analysis of transport data for several other rivers in the eastern United States also indicates that the largest amounts of suspended sediment are carried during the winter months. This is true for Brandywine Creek in Pennsylvania, Perkiomen Creek in Pennsylvania, and the Yadkin River in North Carolina. It appears, then, that those factors which influence erosion of the cohesive riverbank also help to determine the seasonal pattern of erosion on the surface of the drainage basin, particularly in drainage basins of moderate to large size where the variability of stream flow is not at a maximum.

Although the cross-sectional shape of a meandering channel is maintained by erosion of the concave or outer bank and deposition on the convex or inner bank, deposition need not be precisely in phase with erosion. For the channel bank to be built to its maximum height requires discharges of adequate stage. If, for example, the floodplain is overtopped only once each year, then, in terms of the maximum elevation of the floodplain surface, the effective discharge occurs only once each year. In the example from Maryland cited above, this effective "constructional" discharge is less frequent than the effective erosional discharge.

It has been shown (Wolman and Leopold, 1956) that many rivers of all sizes flowing in diverse physiographic and climatic regions attain the bankfull stage once each year or once every two years. This uniform frequency of flooding suggests that, if the regimen of the stream remains constant, no change takes place in the relative elevation of the surface of the floodplain and the bed of the stream. The constancy of the relation indicates that progressive deposition by overbank flows is not responsible for the formation of the floodplain. Instead, the principal mechanism appears to be lateral movement of the channel and deposition of point bars or deposits of lateral accretion. Because the bankfull stage is equal to the elevation of the floodplain surface, and overbank flows contribute only a small part of the floodplain sediment, the bankfull discharge appears to be the "effective" discharge controlling the development of the floodplain. This discharge is attained each year or every other year. Hence, to the extent that these relations hold true, the river floodplain as well as the channel shape is controlled by a force of moderate magnitude which recurs frequently rather than by rare discharges of unusual magnitude.

Within the channel itself, there is a close relation between wave length of bends in sinuous channels and the bankfull width of channel (Leopold and Wolman, 1956). Presumably, flows responsible for making the wave pattern must follow the path of the wave. Because flows well above the banks do not follow the sinuous pattern of the channel itself, the very good correlation between wave length and width is evidence of the fact that both the width of the river and its pattern must be related to a discharge approximating the bankfull stage. These observations indicate, then, that not only the form but also the pattern of the river channel in alluvium is related to events of moderate frequency.

Development of the alluvial land forms described requires that the river be competent to move the materials comprising the bed or banks of the channel. Because few if any channels are composed of unigranular material, there is a range of discharges over which material of different sizes begins to move. Some observations on bank erosion were cited above. Although the complexity of relations in natural channels makes it impossible to define precisely the critical tractive force at which specific sizes of material will begin to move, the following example does provide a rough approximation of the possible range of discharges competent to alter the form of the channel.

TABLE 8

COMPUTATION OF SIZE OF MATERIAL MOVED BY SENECA CREEK, DAWSONVILLE, MARYLAND, AT BANKFULL STAGE

Bankfull Discharge (cfs)	Recurrence Interval (Yr.)	Tractive Force at Bankfull Stage (Lb/sq ft)	Critical Tractive Force (Lb/sq ft)	Size d_s Moved at Bankfull Stage (Ft.)	Per Cent of Bed Material Less than d_s
1,160............	1.01	0.175	$\tau_c=3.5\,d_s$	0.05	25

NOTE: τ = tractive force = γDs; τ_c = critical tractive force (O'Brien and Rindlaub, 1934); γ = 62.4 lbs/cu ft.; D = depth = 4.0 ft.; s = slope = .0007; d_s = grain size.

The longitudinal profile of the bed of a river channel is generally made up of a succession of pools and riffles. At low flow the slope of the water surface consists of alternating flat segments over the pools and steep segments over the riffles. With increasing stage these discontinuities of the water surface tend to be smoothed out. In many natural channels the surface becomes nearly uniform at two-thirds of bankfull to near-bankfull stage. This equalization of slope tends to equalize the tractive force in the pool and in the riffle. On Seneca Creek near Dawsonville, Maryland, for example, computations based on an equation for critical tractive force indicate that the tractive force at a discharge near bankfull stage (table 8) is sufficient to move particles which are equal to or greater in size than 25 per cent of the material on the bed. This size is considerably larger than material making up the floodplain. In this and similar cases, the bankfull discharge is fully competent to move the material required in the formation of the river channel.

The foregoing examples indicate that the floodplain and the shape and pattern of the river channel are related to discharges approximating the bankfull stage. This view is in close accord with the opinions of both Franjii (1946, p. 122) and Inglis (1941, p. 112). As the bankfull discharge recurs on the average once each year or two, it may reasonably be concluded that significant alluvial land forms are formed by frequently recurring events of moderate intensity and not by rare floods of unusual magnitude. Some confirmation of this view is provided by observations following the record-breaking floods of August, 1955, in Connecticut. The effects of the flood in many river valleys were extremely spotty (Wolman and Eiler, 1958). In those places where the flood altered the valley materially, it appears to have destroyed those orderly features produced in the alluvium by the steady working of more moderate flows. These latter flows, rather than the extreme flood, appear to be responsible for the major land forms in stream valleys in Connecticut.

The chronologic details of recent stream history are poorly known. Certain features of channels and valleys seem to bear the marks of inheritance, but, unfortunately, many of these are difficult to separate definitely from the effects of modern stream action. Thus some cases of anomalous valley width have been attributed to underfit or overfit streams. However, there is at present no objective standard for judging the degree of adjustment between sizes of valleys and the channels flowing through them. Another kind of example is that provided by glaciated mountain valleys, where stream channels contain bed material which apparently is too large to be moved by recorded floods (Miller, 1958). Such floodplains as occur are composed mostly of coarse gravels overlain by thin layers of sand and silt. Banks are poorly defined and channels generally lack pools and riffles. These properties may be interpreted as the reaction of a smaller modern stream to materials inherited from a period of greater stream competence which possibly existed during glacial times. Alternatively, catastrophic floods which recur infrequently under modern climatic conditions may be a critical factor affecting such streams. Direct observation of the competence of catastrophic floods is not available, but computations based upon known depths of high water suggest that this explanation is less likely.

FORM AND ORIENTATION OF SAND DUNES

Studies of the relation between dune orientation and wind direction have long included both frequency and magnitude of the wind. Thus Cooper (1958, p. 62) complains that in some explanations of the orientation of longitudinal dunes "emphasis is put upon frequency to the exclusion of other characteristics: velocity and turbulence." According to Bagnold (1941, p. 204), the height of the slip face of a dune is principally determined by the grain size and the wind speed. Because of the relative ease with which a dune can be deformed, its form is a function of a resultant wind made up of those winds which exceed a critical velocity for movement. The form prevailing the largest fraction of the time might be considered the normal or equilibrium one. Because increasing wind speeds occur with decreasing frequency, other things being equal, the form of the hypothetical normal dune should be related to a range of winds somewhat in excess of the competent speed and not simply to the strongest wind.

The rate of movement of sand above the threshold velocity is proportional to the third power of the velocity. Thus for equal periods of time, higher velocities produce greater effects. Bagnold (1941, p. 69) developed a formula to describe the "weighted" resultant wind, which includes the time during which the wind blows from various directions as well as a weighting factor based on the relation between the rate of sand movement and the velocity. Recent studies have shown that seif dunes in southern Israel are aligned parallel to the "weighted resultant wind direction" (Rosenan, 1953, p. 94; 1954). It is interesting to note, in passing, that the direction of the weighted resultant wind may differ considerably from the direction of the so-called "prevailing" wind.

Considering a unidirectional wind, the data in table 6 provide a simple example of the magnitude and frequency of the winds controlling dune form and orientation. All winds shown in the table exceed the critical. The critical velocity required to move the size of particles commonly found in dunes (0.25 mm.) is about 10 miles per hour. A speed of 10 mph at the ground corresponds roughly to from 17 to 20 mph twenty feet above the ground, where wind speeds are more often measured. Winds in class A (table 6) occur far more often than do the greater wind speeds in classes B and C. Net effects of the strongest winds (class C), however, are diminished by their reduced frequency. Without weighting, the product of velocity and time (a crude measure of the sand transported by each class) shows that by far the largest transport occurs in class B. When weighted by the cube of the velocity, maximum transport is still performed by winds in the middle range, but the weighting markedly reduces the per cent of the total sand transported by winds in this class. Cooper (1958, p. 54) does not weight the vectors but suggests that the orientation and form of a set of oblique dunes on the coast of Oregon may be related simply to the resultant wind formed from a parallelogram in which the direction of the vectors is given by the principal wind directions and their magnitude by the wind speed. Weighting tends to increase the proportionate effect of higher wind speeds in both the examples cited. However, net transport of sand, and also dune form and orientation which depend on wind speed and direction, are adjusted to winds which recur often during the year; they are not controlled simply by the isolated rare event of extreme magnitude.

PROFILES OF BEACHES

Many workers have observed that a beach maintains, on the average, what is called an "equilibrium profile." However, like the dune form, and to a much greater degree than the form of a river channel, the profile of a beach is subject to rapid adjustment with variation in conditions controlling beach form. The equilibrium profile, therefore, must be considered as an average form around which rapid fluctuations occur. Waves from storms may periodically destroy the equilibrium form, but over a period of years there is an average equilibrium profile by which the beach may be characterized. The processes which control this profile are our concern here. In the following example an attempt will be made to show that the effective force determining such an equilibrium profile is provided indirectly by frequent winds of moderately high speeds and not by rare storm winds of maximum wind speeds.

The profile of a beach is primarily a function of grain size and the ratio of wave height to wave length. This ratio is designated as the "wave steepness," H/L (fig. 4, *a*). In general, the larger the size of material on the beach, the steeper the slope; and the greater the ratio H/L, the lower the slope (Bascom, 1951; Rector, 1954). For a given grain size, then, the slope is controlled by the ratio H/L. Because wave steepness in part is related to wind speed, a hypothetical example may be used to illustrate the frequency and magnitude of the effective winds controlling the beach profile.

Let the grain size on a given beach be 0.4 mm., a value within the range of beach sands on the West Coast of the United States (Bascom, 1951). Assuming that the beach is perpendicular to the winds controlling the wave steepness, the relation between the wave steepness, H/L, and the general foreshore slope at a constant grain size can be determined from equation (7) of Rector (1954, p. 24). The curve relating the slope of the foreshore to the wave steepness for an assumed grain size of 0.4 is shown in figure 4, *a*. The equilibrium profile for this beach presumably lies somewhere within this range of slope (fig. 4, *a*). For a given range of wind speeds, another curve (fig. 4, *b*) can be drawn relating H/L to wind velocity (U.S. Navy, Hydrographic Office, 1951). The range of wave steepness, H/L, used in the example is similar to the range of values observed by O'Brien (1951) at the Columbia River Lightship off the coast of the state of Washington. These values are also shown in figure 4, *b*.

Observations have shown that during the winter the beach may steepen as a result of short, choppy waves, whereas in the summer it should be expected to flatten. For the material used in his experiments, Johnson (1949) noted that the transition from an "ordinary" to a "storm" profile took place at a wave steepness, H/L, of about 2.5 per cent. Using a value of 2.5, the equilibrium profile in the hypothetical example can be determined from figure 4, *a*. For a value $H/L = 2.5$ at the assumed grain size, the equilibrium beach profile will have a slope of about 0.1. This wave steepness is also associated with a wind speed of about 12 knots (fig. 4, *b*).

At Eureka, California, which is a coastal station not at the most exposed coast, a velocity of 12 knots, here associated with the

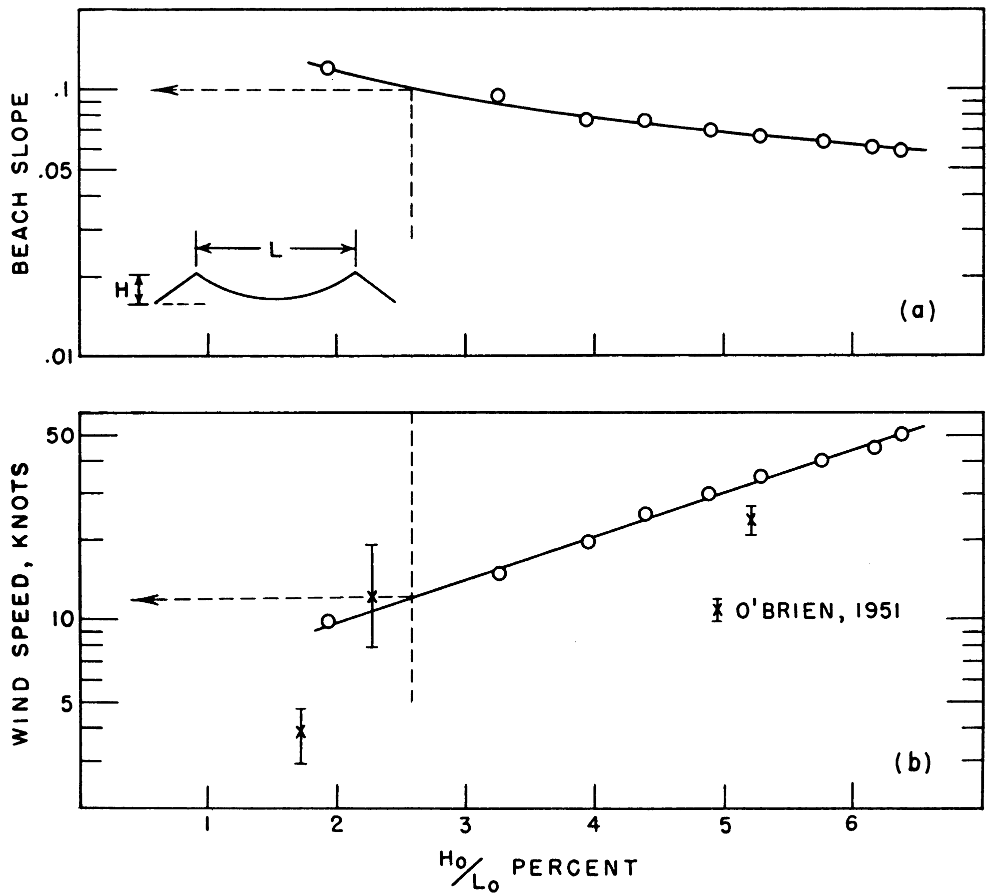

FIG. 4.—Interrelations of wind speed, wave characteristics, and beach slope

equilibrium beach profile, is exceeded by all maximum monthly wind velocities (table 9). This 20-year record indicates that a wind speed of 12 knots will be exceeded as a monthly maximum at least twelve times per year. At a more exposed station—North Head, Washington—the average hourly wind velocity is approximately 13 knots, roughly that associated with the beach profile described here. This example suggests that the effective stress to which the equilibrium profile of the beach is related is one produced by moderately strong winds which generate moderate storm waves rather than by winds which accompany infrequent catastrophic storms.

TABLE 9

CUMULATIVE FREQUENCY DISTRIBUTION OF MAXIMUM MONTHLY WIND SPEEDS AT EUREKA, CALIFORNIA, DURING THE PERIOD 1930–1949*

Maximum Monthly Wind Speeds (Knots)	Cumulative Per Cent of Occurrence Less than Specified Speed
15	2
20	19
24	50
25	60
30	89
35	98

* Data from published records of the U.S. Weather Bureau.

Several observations offer some support for this conclusion. Johnson (1952, p. 950) states that "contrary to popular belief, it is not the relatively steep storm waves that cause a relatively large littoral transport, but rather the intermediate or summer waves which are the major factor in shoreline processes. . . . The greatest transport of sediment along the beach occurs when the beach profile is in equilibrium with waves whose steepness is approximately 0.025." Explaining the fact that the shoreline and offshore depth changes are not as marked as might be expected following a New England hurricane, a report of the Chief of Engineers (U.S. Army, 1950, p. 17) suggests that "the evolutionary processes within the normal tidal range, and under water, where comparisons have been made, have reached a rather mature stage and consequently changes within the rather brief period of historical record are slow and slight, and the level of wave attack during hurricanes has been higher than that most effective in changing the configuration of the shore." A similar observation was made by Nichols and Marston (1939) when they stated that "although the changes caused by the hurricanes of September 21, 1939, were greater than those resulting from many years of winter storms, it seems likely that in a few years the beaches will be in essentially the same condition as they were prior to the hurricane." Data on wave energies given in table 10 likewise indicate that forces that affect beaches are of moderate magnitude most of the time.

TABLE 10

ENERGY TRANSMITTED BY LAKE AND OCEAN WAVES OF TWO FREQUENCIES, CONSIDERING WAVE SYSTEM TO BE UNIDIRECTIONAL*

	Percentage of Total Energy by Waves with Recurrence Interval	
	1 Day per Month	1 Day per Year
Lake Michigan:		
Bailey's Harbor, Wis.	10	2
Milwaukee, Wis.	18	5
Chicago, Ill.	26	2
Muskegon, Mich.	26	7
Frankfort, Mich.	21	3
Lake Erie:		
Monroe, Mich.	32	5
Cleveland, Ohio	19	4
Erie, Pa.	23	1
Buffalo, N.Y.	26	5
Lake Ontario:		
Stony Point, N.Y.	25	3
Atlantic Ocean:		
Penobscot Bay, Me.	16	2
Nauset Beach, Mass.	19	1
New York Harbor Entrance	30	1
Chesapeake Bay Entrance	30	1

* Data are from Saville (Beach Erosion Board Tech. Mem. 36, 37, 38, and 55) for 3 years of record.

SIGNIFICANCE OF CATASTROPHIC EVENTS

In the preceding discussion it has been argued that forces of moderate magnitude and frequency have greater net effect on land-form development than do intense, short-lived forces associated with catastrophic events. Clearly, such a general conclusion requires qualification to the extent that catastrophic events produce results that are (1) unique in some respect because of magnitude or (2) different in kind from effects of more ordinary occurrences. Several illustrative examples are discussed below.

Landslides and formation of new gullies are common occurrences during exceptional storms. Once formed, a gully continues to grow during more moderate storms, and thus the extreme event may have an enduring effect on drainage pattern and topography.

Changes in dimension and position of stream channels commonly occur during large floods. Many such cases were reported following the record Kansas-Missouri floods of July, 1951. Woolley (1946) mentions several cases where channels were downcut several tens of feet and widened a few hundred feet during cloudburst floods in Utah. These trenches, which are too large for the ordinary flows, persist for long periods after the extreme flood. Channel characteristics of many arroyos are clearly related to flows of different magnitude. Deposition occurs during flows smaller in volume than the losses by percolation into the channel; floods large enough to carry the full length of the arroyo cause scour of the channel bed and banks. Extensive migration of bends and meander cutoffs may also be associated with floods. Jahns (1947) cites a case in the Connecticut Valley where destruction of vegetation by exceptional floods in 1936 and 1938 resulted in accelerated bank erosion during later low-water stages. Channel islands of the Connecticut River were destroyed during the 1936 and 1938 floods, but new islands were deposited in approximately the same places as the floodwaters receded. Aggrading streams like the Rio Grande often undergo spectacular channel changes, called "avulsions." Deposition at stages below bankfull continues until the stream is literally flowing on a ridge. Then, during a flood the stream breaks out of its channel and is re-established in a lower part of its valley floodplain, where the building of a new channel ridge commences all over again.

According to Woolley (1946), channels of larger streams in Utah are sometimes dammed temporarily by coarse debris from tributaries. Rio Puerco and Rio Salado occasionally build fans at their mouths which divert the Rio Grande to the opposite side of its valley. Depending on the flow of the main stem, removal of these features may take years. Breaks in the profile of the main stem below tributaries that contribute flood debris apparently reflect downstream progression of sediment waves. Phenomena of this kind are not restricted to arid regions. Jahns (1947) mentions debris fans in the Connecticut River drainage, and they have been observed in other places.

Scouring of floodplains during exceptional floods is often localized. However, some of the features produced in this way are impressive because of their topographic relief. Jahns (1947), for example, describes scour channels and swirl pits 15–20 feet deep formed during the Connecticut River floods of 1936 and 1938. Like floodplain scour, overbank deposition is sporadic and localized. However, a floodwater bar composed of coarse materials, and several feet thick, may be a major topographic feature of the floodplain. A special kind of case requiring extreme flood conditions is deposition on high terrace surfaces. Such deposition has been reported in several Eastern stream valleys, among them the Connecticut (Jahns, 1947; Wolman and Eiler, 1958) and the Susquehanna.

Extreme floods accomplish transport of material that is impossible by more ordinary flows. For example, Woolley (1946) reports that huge boulders weighing more than 100 tons have been moved long distances on gentle slopes by mudflows in Utah. Countless comparable examples, from southern California, Arizona, and many other places, could be cited. With regard to the sizes of materials transported, the effects of floods appear to be directly proportional to their magnitude. This implies that alluvial fans owe many of their properties to extreme rather than moderate flows, although the frequency relations of stream flows and mudflows have not been adequately defined.

The previous discussion of equilibrium beaches emphasized seasonal variations. In many places during the summer, beaches build seaward, are composed of finer material, and have flatter slopes than during winter when they are eroded by higher waves. Where marine cliffs are fronted by broad beaches, erosion of the cliff may occur only during periods of extreme wave action. Barrier islands, which are more or less stable under ordinary conditions, may be eroded below mean tide level during extreme storms. Similarly, along shores of low coastal plains, building of beach ridges several feet above mean low water occurs only during infrequent events of great magnitude.

Because of their relative familiarity, an exhaustive enumeration of examples of the effect of infrequent catastrophic events on the landscape has not been given here. Placed in the context of the earlier discussion, these examples principally illustrate the known thesis that the rare or infrequent events become increasingly important as the threshold stress (competence) required to move the available masses of material increases.

CONCLUSIONS

The observations described in this paper suggest that the effectiveness of processes which control many land forms depends upon their distribution in time as well as their magnitude. It cannot be assumed that, simply because of their magnitude, the rare or infrequent events must be the most significant. Analyses of the transport of sediment by various media indicate that a large portion of the "work" is performed by events of moderate magnitude which recur relatively frequently rather than by rare events of unusual magnitude.

Examples which suggest the way in which some specific land forms are controlled by events of moderate magnitude and frequency were cited. The examples of land forms described in these terms are almost exclusively depositional. For the lone exception, the erosion of a cohesive river bank, a complex combination of conditions actually determines the frequency and magnitude of the principal effective stress. However, these two kinds of cases are related in that the depositional examples and those involving a combination of factors are indirectly determined through the control of the critical or threshold value.

There is a notable lack of examples demonstrating effectiveness of moderate events of frequent occurrence in molding erosional land forms. However, it seems apparent that in many valleys rivers scour to bedrock only during high and relatively infrequent flows. Similarly, from a dynamical standpoint, the movement of large boulders and the erosion of hard bedrock obviously require stresses which are attained during large floods occurring at relatively infrequent intervals.

As an example of the cohesive river banks shows, the threshold of erosion may also be modified by the complex interaction of several factors. The relative effectiveness of various climatic events is generally more complex than that measured in the examples given here. Pre-wetting of bare soil, by reducing the threshold, may prepare the soil for erosion. In most cases a given land form is related to several processes, each of which in turn is controlled by the interaction of precipitation, temperature, and vegetation. For example, the threshold of erosion of sand dunes may be markedly increased by the establishment of vegetation on the dunes. More often than not, however, as in the semiarid regions, the relation between climate, vegetation, and erosion is less direct. In a given region processes of diverse character control individual features of the landscape. The magnitude and frequency of the events responsible for one feature may be very different from the magnitude and frequency of events responsible for another.

Evaluation of the relative importance of various geomorphic processes in a given region, as well as the relative effectiveness of events of different frequency, will require more detailed observations of the land forms themselves and of the processes operative on them.

Perhaps the state of knowledge as well as the geomorphic effects of small and moderate versus extreme events may be best illustrated by the following analogy. A dwarf, a man, and a huge giant are having a woodcutting contest. Because of metabolic peculiarities, individual chopping rates are roughly inverse to their size. The dwarf works steadily and is rarely seen to rest. However, his progress is slow, for even little trees take a long time, and there are many big ones which he cannot dent with his axe. The man is a strong fellow and a hard worker, but he takes a day off now and then. His vigorous and persistent labors are highly effective, but there are some trees that defy his best efforts. The giant is tremendously strong, but he spends most of his time sleeping. Whenever he is on the job, his actions are frequently capricious. Sometimes he throws away his axe and dashes wildly into the woods, where he breaks the trees or pulls them up by the roots. On the rare occasions when he encounters a tree too big for him, he ominously mentions his family of brothers—all bigger, and stronger, and sleepier.

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