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EARTH SURFACE PROCESSES, VOL. 3, 189–208 (1978)

# RELATIVE SCALES OF TIME AND EFFECTIVENESS OF CLIMATE IN WATERSHED GEOMORPHOLOGY

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## SUMMARY

Peak rainfalls and peak runoff rates per unit area are comparable over a worldwide spectrum of climates. However, while the magnitude of the external contribution of energy or force in diverse regions is similar, the impact on the landscape varies markedly between regions. Absolute magnitudes of climatic events and absolute time intervals between such events do not provide satisfactory measures of the geomorphic effectiveness of events of different magnitudes and recurrence intervals. Although geomorphic processes are driven by complex sets of interrelated climatic, topographic, lithologic, and biologic factors, the work done by individual extreme events can be scaled as a ratio to mean annual erosion and the effectiveness of such events in forming landscape features can be related to the rate of recovery of channel form or mass wasting scars following alteration by the extreme event. Thus, a time scale for effectiveness may relate the recurrence interval of an event to the time required for a landform to recover the form existing prior to the event.

River channels in temperate regions widened by floods of recurrence intervals from 50 to more than 200 years may regain their original width in matters of months or years. In semi-arid regions, recovery of channel form depends not only upon flows but upon climatic determinants of the growth of bottomland vegetation resulting in variable rates of recovery, on the order of decades, depending upon coincidence of average flows and strengthened vegetation. In truly arid regions the absence of vegetation and flow precludes recovery and the width of channels increases in drainage areas up to 100 $\mathrm{km}^2$ but remains relatively constant at larger drainage areas.

Area as well as time controls the effectiveness of specific events inasmuch as the likelihood of simultaneous peak discharges or rainfalls and large areas is less, particularly in arid regions where events spanning areas of more than several thousand $\mathrm{km}^2$ are extremely rare if experienced at all. To some extent a decrease in area in a humid region is comparable with a regional change from humid toward more arid climate reflected in the increase in importance of episodic as contrasted with more continuous processes. Exceedingly rare floods of extreme magnitudes, estimated recurrence intervals of 500 years or longer, may exceed thresholds of competence otherwise unattainable in the 'normal' record resulting in 'irreparable' transformations of valley landforms.

Denudation of hillslopes by mass wasting during relatively rare events can also be related to mean rates of denudation and to recovery of hillslope surfaces after scarring by different kinds of landslides. Measured recovery times described in the literature vary from less than a decade for some tropical regions to decades or more in temperate regions. Recurrence intervals of high magnitude storms which trigger mass wasting range from 1 to 2 years in some tropical areas, to 3 or 4 per hundred years in some areas of seasonal rainfall and to 100 or more years in some temperate regions. The effectiveness of climatic events on both hillslopes and rivers is not separable from gradient, lithology or other variables which control both thresholds of activity and recovery rate.

KEY WORDS Drainage basins Time scales Climate Extreme events Response times

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## CLIMATE AND WATERSHED PROCESSES

The geomorphic importance of a given event is governed not only by the absolute magnitude of the force or energy which it brings to bear on the landscape, but also by the frequency with which it recurs, the processes during intervening intervals between such recurrences, and the work performed during such intervening intervals. The combined effect of all events and processes constitutes the assemblage of climatically controlled processes upon which the concepts of effective force and morphogenetic regions rest. Because of the variety of possible combinations of processes and earth materials similar or convergent landforms may result from different combinations or sequences of processes acting on different materials. As Birot (1968) noted, the interrelationship of the many geomorphic processes constituting a climatic geomorphology is exquisitely complex and unlikely to be described by any simple quantitative relationship. At the same time, attempts at understanding such relationships underlie explanations of geomorphic evolution including responses to climatic change, and current attempts to predict the environmental impacts of intentional and inadvertent alterations of the environment by man.

While recognizing that fundamental factors such as topography, structure, and lithology must enter into the comprehensive explanation of the form of any particular landscape, this paper attempts to draw together some illustrative examples to suggest how the 'relative' timing and 'relative' magnitude of landforming events may affect selected landforms in different climatic regions. Both time and spatial scales enter into the determination of effectiveness. In dealing with regions as a whole, it is often convenient to assume that an event recorded at a point in space could or will, over time, occur elsewhere in the region. Such an assumption of regional similarities permits extrapolation of the time or frequency characteristics of a long-term record at one point to the region as a whole; a concept contained in the ergodic theorem which assumes that 'an infinitely long record at one point has the same statistical properties as a record taken over an infinite number of spatial ensembles at a particular point in time' (Harvey (1968, p. 77)). It is also true, however, that the importance of a given event or sequence of events in moulding the landscape will vary with the spatial distribution of the event, such as a rainstorm, and with the scale or size of the drainage basin and landforms upon which it acts. The ergodic assumption is implicit in the generalizations suggested here, and attention is drawn to the importance of the spatial scale.

### *Definition of effectiveness*

In attempting to evaluate the effectiveness of climatic elements in geomorphology, a distinction has been made between work performed and sculpture of the landscape (Wolman and Miller (1960), Thornbury (1954)). Work has customarily been measured in terms of the quantity of material transported over a given distance in a given period of time using data on the clastic and dissolved load in rivers, or products of mass wasting or sheet wash from hillslopes (Rapp (1960)).

Movement of large quantities of material from hillslopes is not necessarily synonymous, for example, with incision of gullies on the same landscape. Rare events of large magnitude may create new gullies during short duration downpours, but over long periods of time the total quantity of sediment removed from the hillslope may be considerably greater than the amount removed in cutting the gullies. We are concerned here primarily with *formative events*, those occurrences which shape the landscape and in some cases with the net denudation of specific meteorological events.

*Effectiveness* then is here defined in terms of the ability of an event or combination of events to affect the shape or form of the landscape. This landforming result is only partly related to the mass of material removed. Because the form of many features of the landscape is controlled by both destructive and constructive processes, the effectiveness of a destructive event depends upon the force exerted, the return period of the event, and upon the magnitude of the constructive or restorative processes which occur during the intervening intervals. That is, the importance of events which sculpture the landscape is measured, in part, relative to the processes which tend to restore the surface of the landscape to the condition existing before the new landforms were created. In some instances, when an event of rare occurrence and high magnitude creates new gullies, widens major river channels, or lowers the gradient of hillslopes by eroding the upper surfaces and depositing downslope, the newly created features of the landscape may persist for very long periods of time, or, during succeeding intervals less dramatic processes of more frequent occurrence may begin to 'repair' the changes and to restore landforms existing prior to the instantaneous resculpturing. Over a period of time recovery may be complete and hillslopes and streams return to forms which are maintained over the greatest part of the life of the landform. Effectiveness then cannot be defined in absolute terms related to frequency or rarity and magnitude of force but must include a relative scale differentiating the force and result of instantaneous or short-lived events as contrasted with the time interval required for the landscape to reform.

A comprehensive definition of effectiveness of processes or climate in geomorphology would include the denudation as well as landforming effects of various combinations of processes over time. From the standpoint of the landscape as a whole, denudation may be continuous but the form or shape of the landscape is retained for long periods of time (see Chorley (1962), Schumm and Lichty (1965), for caveats about how long is long). Effectiveness is not solely related to denudation, not only because this ignores the form of the landscape, but because denudation and products of erosion are not uniformly distributed in space or in time on the landscape. If measurements of sediment delivery ratios, for example, are to be believed at all (Roehl (1962)) then it is clear that large quantities of sediment removed from the upper parts of a drainage basin either accumulate at the base of hillslopes or in floodplains and stream channels, inasmuch as quantities of sediment measured at downstream locations are considerably less than amounts apparently eroded from upstream sources. Both the location and timing of erosion differ from place to place on the watershed. Thus the effectiveness of a given climatic event will vary with the size of the area and the movement of material will be sequential in character from place to place and hence from time to time.

The following descriptions of some hillslopes and river channel processes are intended to illustrate the way in which both the magnitude of an event and its effectiveness must be related to the mean conditions of climate and process in a given region. The importance of an event with a frequency of once in one hundred years in sculpting the landscape need not be the same in two different regions. Its significance will differ depending in part upon the characteristics of the climate, position within a watershed, and processes during the intervening intervals between such rare events.

## SPATIAL CHARACTERISTICS OF RAINFALL AND RUNOFF

For many years it was assumed that because of their apparent intensity desert rainfall and runoff were more intense and runoff swifter in the arid regions than in humid temperate or tropical regions. More accurate data, however, revealed that such differences were apparent, not real. At the same time, evidence has accumulated which may permit some generalizations relevant to the climate and hydrologic factors determining the impact of specific geomorphic processes. Space as well as magnitude and timing affect these processes.

### *Area and intensity*

Rainfall depth, intensity, duration and degree of synchronization of rainstorm cells decrease with increasing rainstorm area, and the relative effectiveness of rainfall events should be expected to decline with increase in area—relationships between surface area and climatic variables may be inversely proportional. This can be illustrated both in arid areas where frequently occurring cells of rainstorms do not exceed 10 km in diameter (Sharon (1972)), and in semi-arid zones where characteristic storm diameters are 10–20 km (Fogel and Duckstein (1969)) and the more intensive core—7–10 km (Osborn and Laursen (1973)). A characteristic of thunderstorm-affected regions is that the higher the intensity of a rainfall cell, the more limited is its area (Osborn and Laursen (1973)).

In humid regions, such as the Atlantic provinces of the United States, the occurrence of precipitation areas of various scales is more complex (Austin and House (1972)) and relationships between cells, 'background' rainfall, and flow events cannot be readily generalized. However, rainfall cells are also well documented in tropical regions (Temple and Rapp (1972, p. 164)). Similarly it is known that peak discharge per square mile decreases with increasing drainage area and a similar inverse relationship exists between drainage area and the ratio of a high magnitude flow event to mean annual flood (Kuiper (1957)).

There is a distinct difference in the effectiveness of diverse rainfall events of similar frequency on hillslopes and on adjacent low order streams both in arid and humid climates. In humid regions, the headwaters of larger perennial streams are often ephemeral and first order tributaries approaching a divide tend to dry up. Frequency of surface runoff is very low on hillslopes and in first order streams compared to higher order ones. In arid and semi-arid zones, frequency of flow may be higher on hillslopes than in adjacent streams, as much of the potential overland flow percolates into accumulations of colluvium downslope and into sediments in the channel bed (Yair and Klein (1973), Yair (1972)). Over larger areas, however, as one moves downstream in arid watersheds, frequency of flows may increase, as illustrated by Diskin and Lane (1972) for southeastern Arizona where, on the average, twelve flow events per rainy season were experienced on 100 km$^2$ catchments, as opposed to six events for 2·5 km$^2$ watersheds.

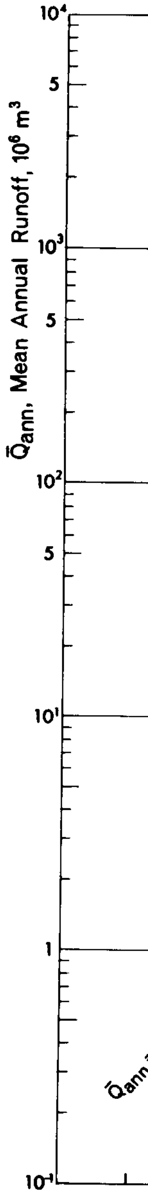
### *Partial area activity*

Partial area activity, both in process and change of form, is characteristic of most climatically induced events in watersheds under all climates. The more humid the climate, the higher the degree of synchronous activity we should expect for a watershed, be it small or large. In small drainage basins in both humid and arid areas during moderate rainfall events, the areas contributing runoff or sediment are close to channels (Dunne and Black (1970), Artega and Ranz (1973), Yair and Lavee (1974)). During events of higher magnitude, the contributing area becomes progressively larger. The higher the magnitude of an event, the more integrated are the processes affecting transport and landforms.

On larger watersheds (tens to thousands of km$^2$ in area), rainfall cell size, spottiness of occurrence and intensity become most important. Both the space effectively covered by a single storm and the synchroneity of rainfall occurrence decrease with aridity. In arid zones, integration of drainage systems occurs mainly during extremely rare intensive events covering the drainage basin, as in Tunisia in 1969 (Clarke (1973)). In contrast, as a rule generalized rainfall over larger areas in humid regions is not confined to rare events, but covers the spectrum from low precipitation to high and sustained precipitation over large areas. In neither case does it follow that the integration and continuity of landscape elements, such as channel or hillslope forms, result from a single major event. This is most obviously seen in the process of channel incision through headcut retreat. Various facets of the watershed have different thresholds of erosion and these may or may not be exceeded during a single event, although each may require a 'large' event to trigger a response. However, it remains difficult to point to threshold values of rainfall intensity and duration for an integrated activity on even a very small watershed. An intensive storm of February 1975 which generated several flood flows in the Nahal Yael Experimental Watershed, southern Israel, is an example. The drainage area is 0·7 km$^2$ and mean annual precipitation is 25 mm. The storm yielded 80 mm of rainfall in less than 12 hours, but still no synchroneity of flow nor integrated activity could be observed; different hillslopes and channel tributaries flowed at different times. Tricart (1960) has referred to discontinuities of sediment movement in streams, in all likelihood, the integrated drainage net represents the result of a very large assemblage of events discontinuous in time and space.

### *Similarities and differences in stream flows in different climates*

It is well known that mean annual stream flow increases progressively with drainage area in humid regions (Figure 1). Although discharge per unit area is less, many streams in subhumid to semi-arid areas such as parts of Colorado and California show a similar increase (Figure 1). While mean annual flow in ephemeral streams in California also increases downstream, the rate of increase is considerably



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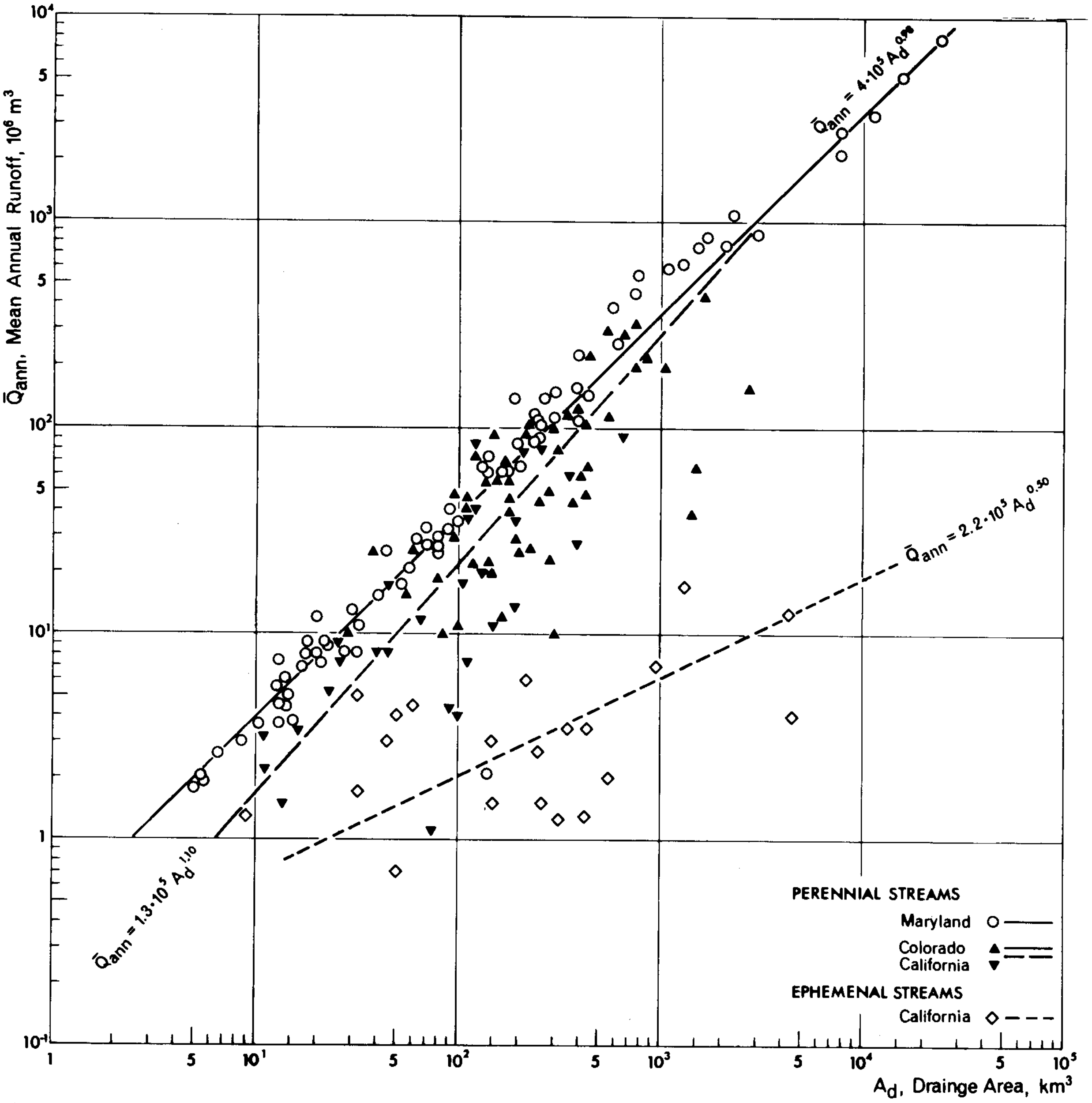

Figure 1. Relation between mean annual runoff and drainage area for streams in humid, semi-arid and arid regions, including perennial and ephemeral streams (sources of data: Hedman (1970, Table 1), Hedman *et al.* (1972, Table 1), Walker (1971)

lower (Figure 1). Some decline in rate is also suggested in the transition from subhumid to semi-arid streams.

Perhaps even more interesting is the similarity of maximum discharges per unit area for climatic regions ranging from arid to very humid (Figure 2). Within the general uniformity, data from the arid and semi-arid zones available here, however, indicate that discharge per unit area is higher in the southwestern United States than in comparable climatic regions represented in Figure 2. This systematic difference may be related to the fact that there is more data and from longer records in the southwest United States, or to differences in the types of precipitation regimes involving thunderstorms, seasonal and/or orographic effects.

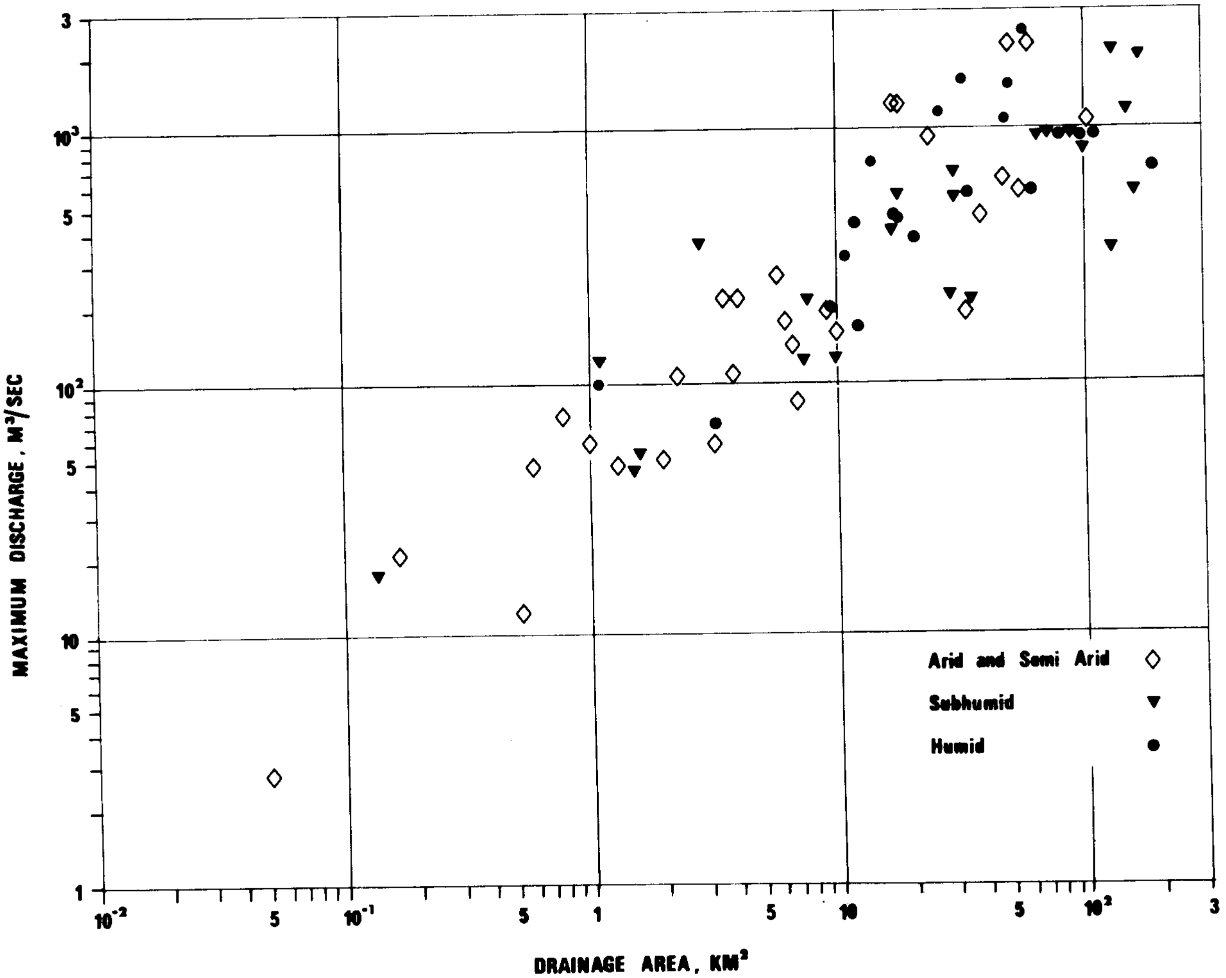

Figure 2. Relation between maximum discharge and drainage area in arid, semi-arid, subhumid and humid regions (sources of data: Creager *et al.* (1944), Dalrymple (1964), Jarvis (1942), Schick (1968), Inbar (1972), Gerson (1972), TVA (1961), Matthai (1969), Aldridge (1970), Rostvedt *et al.* (1970), Glancy and Harmsen (1975), Matthai (1977), Thomas (1973)

Differences in maximum runoff from a single severe storm in different physiographic settings may also be insignificant. Confirming the adage that floods are caused by too much rain, yields in the Appalachian Valley and Ridge, piedmont and coastal plain provinces during Hurricane Agnes in June, 1972, are similar for a given drainage area (Figure 3).

Envelope curves such as those in Figures 2 and 3 mask or encompass a multitude of variations. At the same time, the marked similarity of maximum discharges throughout the world leads to speculation regarding the way in which river channel processes in these markedly different regions respond to high magnitude events of rare frequency and to 'normal' day to day events. While rainfall intensities and maximum discharges are quite similar in different regions, their effectiveness as formative agents on channels and hillslopes is not.

## RIVER CHANNELS

The notion of equilibrium in river channels is based on the assumption that over a period of time the net effect of a variable climatic regime will produce a river channel of a given size and shape which is termed to be in adjustment with the climatically controlled runoff, sediment and vegetation

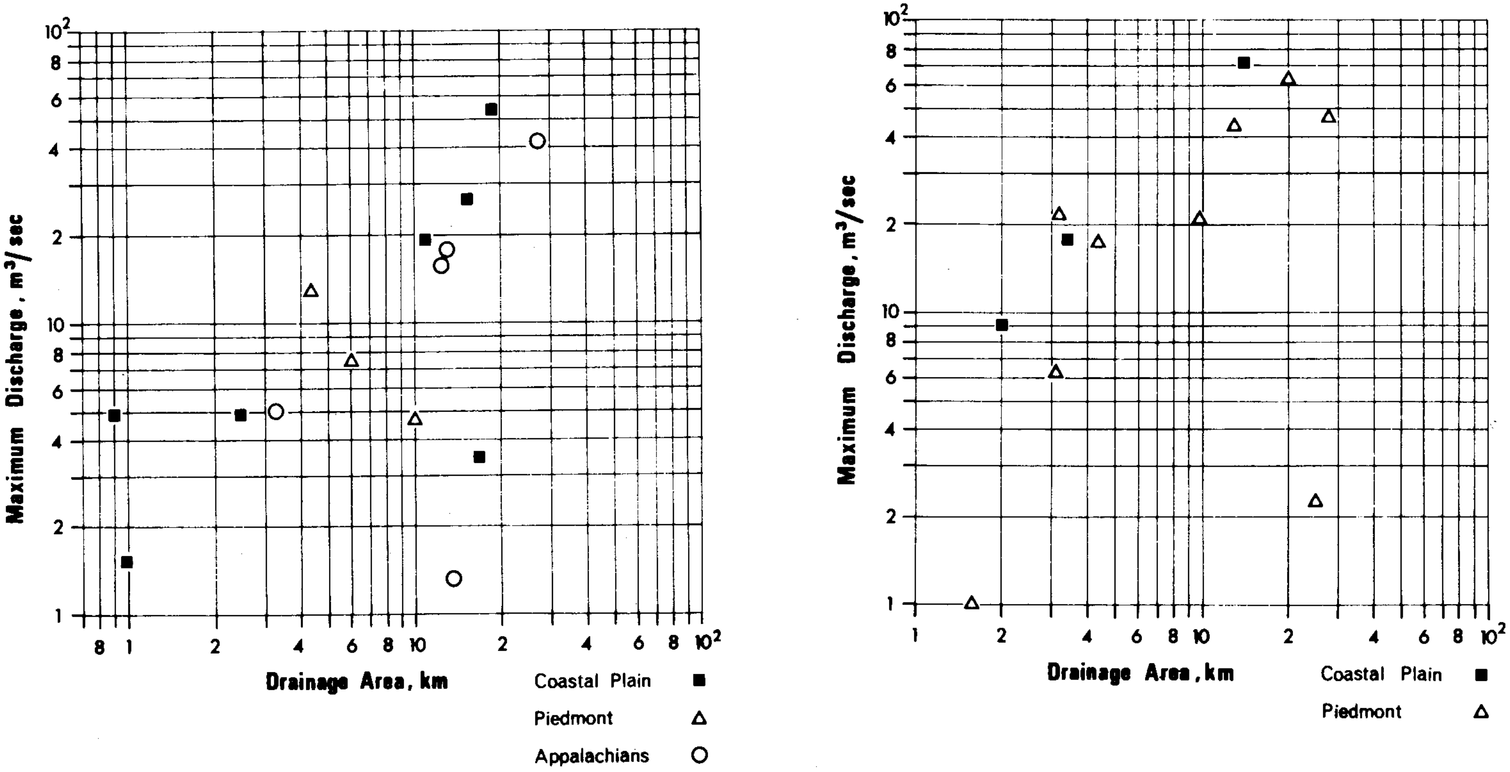

Figure 3. Maximum discharge in relation to drainage area in three different physiographic provinces for a 200-year storm in June, 1972, in the Appalachian region of Maryland and Pennsylvania (source of data: Taylor (1972))

within a given geological setting. All definitions recognize that both the processes and specific forms represent averages and that the characteristics which define equilibrium must be measured 'over a period of years', in Mackin's (1948) phrase, to allow for short-term variations. The 'equilibrium' of a stream at a given point will, over time, fluctuate around a mean. The effect of climatic change is discernible only when a trend in the width, or in any other descriptive parameter can be detected, or when a 'new' form is maintained for a sufficient period of time to permit distinction between the previous and the newly established values.

Observations of the response of river channels in different climates and flow regimes to floods of different magnitude indicate differences in both the significance of a flood of a given magnitude on the characteristics of the channel and on the *recovery period*. Logic suggests that if the rate of revegetation in a given region, primarily dependent on moisture, is rapid, then regardless of the destruction of the river channel wrought by individual floods, assuming a supply of sediments, one should expect relatively rapid recovery of vegetation and hence reconstruction of channel characteristics prevailing prior to the high-magnitude event. In contrast, in desert regions where vegetation is rare and growth minimal, destructive floods should essentially produce nearly irreparable and hence progressive changes. Several illustrations support this generalization.

During Hurricane Agnes the channel of the Patuxent River, Maryland, was widened in places by many metres (Gupta and Fox (1974)). Expressed in terms of per cent change in width, values range from 10 to 40 per cent. Observations made at a number of locations along the Patuxent River prior to and following three floods of roughly 200-year, 100-year, and 50-year recurrence intervals indicated that in this region of roughly 1,000 mm of precipitation and a mean annual flow of $0{\cdot}011\ \mathrm{m}^3/\mathrm{km}^2$ (1 cfs per square mile), vegetation began to be re-established within weeks following destructive floods. The combination of modest increases in discharge accompanied by higher concentrations of fine-grained sediment, and deposition of sediments on bars and near banks exposed during preceding floods initiated reformation of channel width and form. In straight reaches Costa (1974) noted that increases in width produced by floodwaters were not wholly compensated for by immediate deposition. It took more than 12 months to recover width to pre-flood dimensions. Reformation was more rapid, about six months, in somewhat sinuous channels. Present observations of channels in the Piedmond, Mid-Atlantic region, suggest that channels will be restored to former character in a matter of months to perhaps 10 years following disturbance by major floods. This response is shown in Figure 4 where the mean and variations in width along the Patuxent River are plotted along with the magnitude of the change in width created at selected localities during Hurricane Agnes.

In a mountain region, central Appalachians, Hack and Goodlett (1960) noted that channels in small valleys, $0{\cdot}25$–$25\ \mathrm{km}^2$ of drainage area, widened some 300–400 per cent in a single flood, generated by a high magnitude rainstorm (recurrence interval approximately 100 years) in 1949. Within a period of several years, healing of channels was underway, with forest vegetation recolonizing floodplains and channel bars.

Baisman Run, at a drainage area of $4{\cdot}0\ \mathrm{km}^2$, shows a similar response to that observed in the Patuxent River (Figure 4) and in Western Run (Costa (1974)). Floods of sufficient magnitude to erode the channel banks are experienced on the order of once every 2–5 years in this small Piedmont stream. Channel width is on the order of 3–7 m. Mapping of the vegetation on channel bars and successive measures of channel width indicate that revegetation and deposition of sediment cause the channel to narrow within a period of 1–8 years following destructive floods and movement of gravel.

In contrast to the larger rivers, however, channel processes in Baisman Run are truly episodic. During the greater part of the year the low but perennial flow is insufficient to rework the coarse cobbles found on the bed of the channel. While at least 50 per cent of total transport from the basin is in solution (Cleaves *et al.* (1970)), channel form is entirely dependent on intermittent high flows. Observations over a period of 5 years revealed that, on the average, approximately 14 'events' per year are capable of transporting the gravels and sands found on the bed of the channel. At a drainage area of $0{\cdot}4\ \mathrm{km}^2$ (100 acres) each event such as a summer thunderstorm may range in duration from a few minutes to 1 hour. The cumulative time or duration of flows sufficient to modify the bed of the channel

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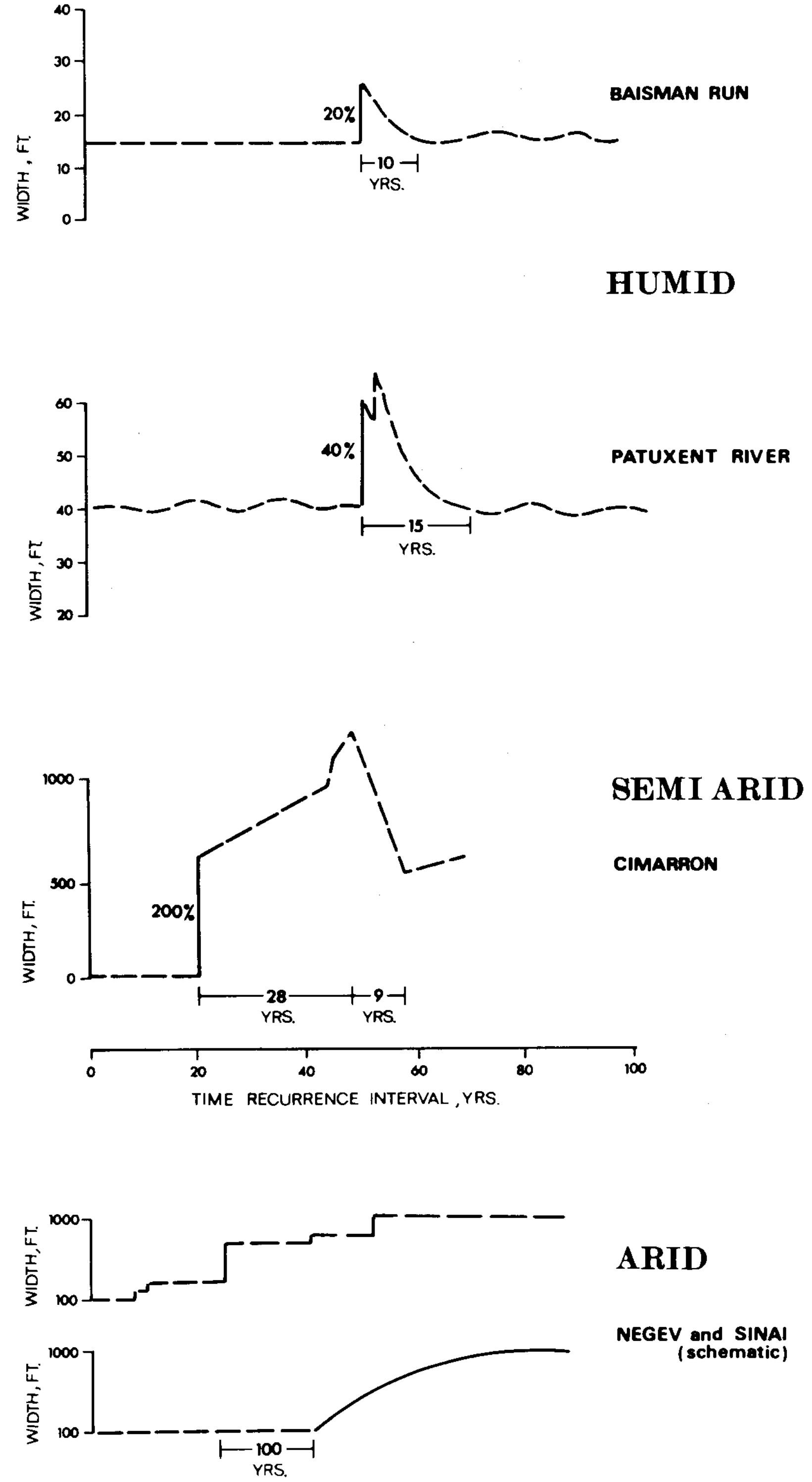

Figure 4. Sequence of changes in channel width showing recovery periods following large storm events and climatic variations for selected rivers in different climate regions. Initial increase on Cimarron River during major flood, followed by continued widening during dry period. Second jump in width due to smaller flood in dry period. Declining width during moist period and vegetation regrowth (Cimarron River curve after Schumm and Lichty (1963). Reference in text including discussion of schematic example from arid regions

is approximately 7–10 hours per year or about 0·1 per cent of the time. In this sense, less frequent events are more significant in modifying the smaller channel than the larger streams within the same region. However, the dense forest vegetation coupled with the ample supply of moisture permits revegetation and recovery at a rapid rate in both the large and small streams.

In contrast to the reasonably stable response of a river in a humid environment, Schumm and Lichty (1963) described variations in width of the Cimarron River in a semi-arid region over a period of years (Figure 4). They conclude that the width of the river narrows during relatively wet periods when vegetation is established in the absence of major floods. However, if a major destructive flood follows upon a period of dry years, when vegetation is reduced on the channel margins, channel width is greatly increased. During the period of dry years vegetation does not become established on the channel margins and the channel width remains large. A decrease in width takes place during wet years when vegetation becomes established and sediments are trapped by the vegetation. Wolman (personal observation) has observed a similar sequence of channel filling and narrowing with progressive increase in rainfall and runoff in small channels in Oklahoma. Sequential changes in the width of the Gila River in semi-arid Arizona also show fluctuations similar to those in the Cimarron. Burkham (1972) concluded that widening was associated with major floods carrying relatively little sediment and narrowing and floodplain reconstruction occurred during periods of low floods carrying higher sediment loads. Roughly 45 years intervened between the advent of two successive floods which widened the channel from several hundred feet (60–100 m) to 2,000 feet (610 m) with intervening periods of widening and contraction. (See Stevens *et al.* (1975), who suggest that the Gila River history is evidence of non-equilibrium.)

At the opposite extreme from the humid tropics and temperate regions, in the desert rainfall and runoff may measure no more than a trace in a period of years. However, very large rainfall and runoff measured in terms of depth per unit time or discharge per square mile in desert regions are comparable to those observed in more humid areas (Figure 2). Desert rainfall and runoff, however, are not distributed uniformly over large areas, and hence in most instances local, high intensity storms produce run-off which may be lost into stream channels as flows move downstream in dry channels (Schumm and Hadley (1961), Osborn and Laursen (1973)). Thus an entire large drainage basin rarely, if ever, experiences runoff from the same meteorological events as is the case in snow melt flooding or during some major tropical storms in humid regions.

In the absence of moisture and vegetation, flood discharges which erode the bed and banks of channels in arid regions leave a virtually permanent imprint on the landscape, unless perhaps altered by aeolian action. Both the episodic character of runoff and the absence of intervening periods of moisture sufficient to promote dense vegetation prevent the channels from being 'restored' to conditions which may have existed prior to the flood event. This succession of changes, because of the long period of time involved, cannot be documented at any one place. However, the major floods in Tunisia (Clarke (1973), Stuckmann (1969)) widened channels in small watersheds as much as 100–400 per cent and in larger ones 30–60 per cent. Observations by Gerson in the Sinai Desert in the Middle East have similarly shown widening of as much as 100 per cent during individual storms.

In humid and subhumid regions, the rate of increase in average bankfull width with increase in catchment area is almost constant (Figure 5). Temporary and local widening by high magnitude floods does not change the pattern, from which we conclude that restoration of channel width after perturbations is relatively rapid in humid regions. Measurements of width only are used because data for other variables are unavailable for desert regions. A different trend is observed in arid watersheds; the rate of increase of width is higher than in humid regions in small watersheds up to a drainage area of 100 km$^2$. In larger areas, channel width remains almost constant. This may be attributed to several factors acting alone or in combinations.

1. Effective storm sizes are not large—10–100 km$^2$—and simultaneous runoff from a larger drainage area is only rarely achieved in arid zones.
2. Channels may be widened by extreme flows until they are wide enough to accommodate the largest available discharges.

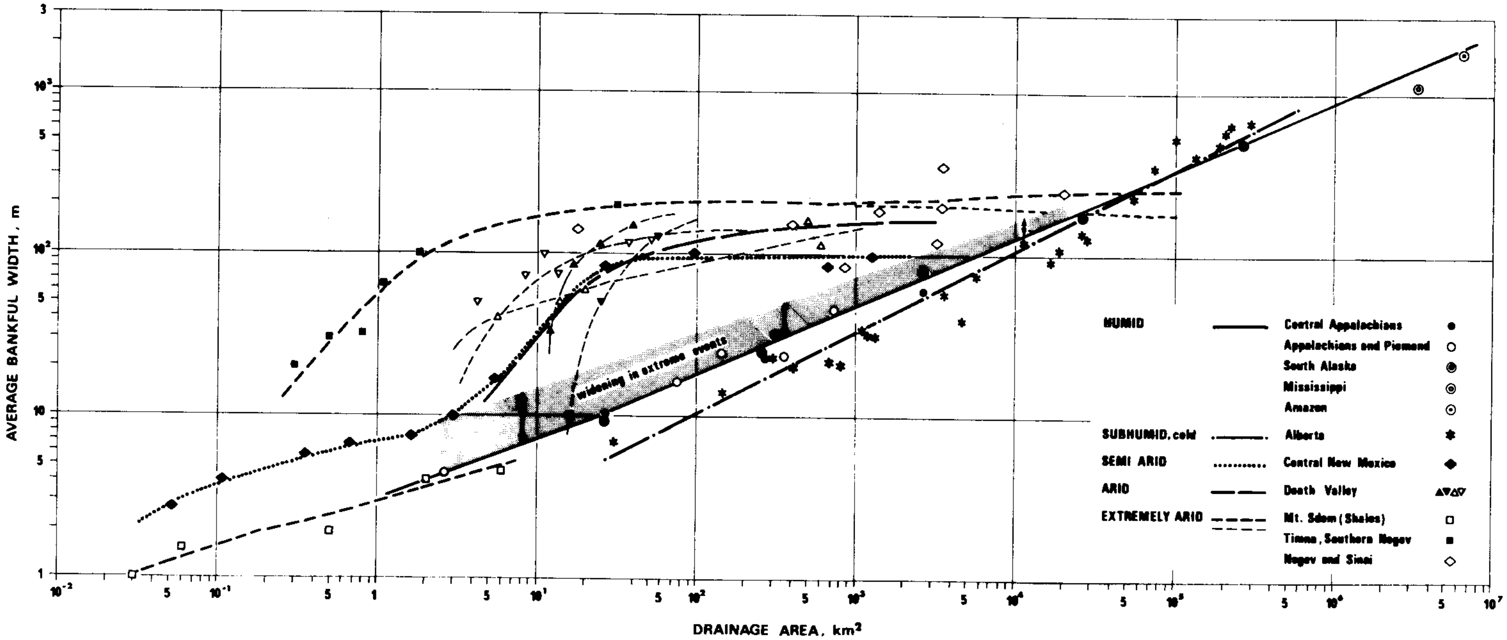

Figure 5. Change in channel bankfull width with increasing drainage area showing progressive increase in humid and subhumid regions, high rates of increase in headwaters and flattening as drainage area further increases in arid regions. Semi-arid channels appear to be intermediate between the rates typical to humid and arid ones. (Sources of data: Central Appalachians—Hack and Goodlett (1960), Appalachian and Piedmont—Wolman (1955), South Alaska—Emmett (1973), Alberta—Kellerhals *et al* (1972), Central New Mexico—Leopold and Miller (1956), Miller (1958)

3. As channels—typically braided—grow wider, the probability of bank erosion by low flow decreases, and the significance of such flows decreases with time.
4. No recovery of width takes place in truly arid regions where vegetation is absent.
5. There may be a transmission loss as the available water sinks into the channel sediments and discharge values diminish or increase at a slower rate.

Figure 5 also indicates that channel width is highly variable at any given drainage area. The shape of the curve for the arid region is taken to be representative, not solely of an increased width with drainage area, but of the progressive increase of width with time at any given location. This relationship is suggested schematically in the bottom sketch in Figure 4 where width is shown to increase progressively with time at a slower rate as width becomes large. Higher rates of loss of water in infiltration into the widening channel bed may contribute to the slower widening.

The one example available from a semi-arid watershed falls with channels in humid regions at a small drainage area, and with those in arid regions at larger drainage areas (dotted line in Figure 5). The arid zone channels may often be wider than ones in humid regions at the same drainage area. This 'accumulative width' is in fact larger up to drainage areas of about $10^5$ km$^2$; however, in humid regions the width of channels draining still larger areas appears to be greatest. This, of course, is in part due to the fact that the world's largest rivers increase in flow downstream.

The effect of lithology in arid zones may change characteristics otherwise dictated by climate. In desert watersheds underlain by shale, surface lithology may transform channel behaviour from that of an arid stream into a humid one. Mt. Sdom, at the Dead Sea, provides a striking example. Although in an extremely arid region receiving only 50 mm/year of precipitation the correlation of width and drainage area (lower line of Figure 5) is similar to that in humid environments. The cause appears to lie in the imperviousness of the terrain and associated dense drainage net developed on the shales which makes them more 'humid' hydrologically.

In terms of channel form, the effectiveness of an event of a given absolute magnitude and recurrence interval becomes progressively less as one moves from the humid to the arid region. The effect is the same in moving from large to small watersheds. A similar analogue of climate and size is evident in the relative proportions of clastic and dissolved load carried by rivers (Leopold *et al.* (1964)): the proportion of clastics increases with relative aridity and in smaller drainage areas. Effectiveness declines, not because of the magnitude or force of events, but rather because of the recuperative capacity of the channel which depends upon the availability of moisture and of vegetation.

### *Thresholds: non-recovery*

The impact of a number of 'catastrophic' floods has been documented in the past several decades. Headwater tributaries of the Vistula River in Poland scoured bedrock up to 1·5 m during a flood of 100 m$^3$/s from an area of 53·4 km$^2$. During intervening periods channel pools and sediment banks are created by lesser flows, but the erosive work of the major event is not obliterated (Brykowicz *et al.* (1973)). Floods on the Guil River (Tricart (1960)) in the Alps in June 1957, (1000 m$^3$/s) with an estimated recurrence interval of 500 years or more completely reworked sediments and valley hillslopes not known to have been altered in more than 300 years of historical record, and perhaps not since waning of the Pleistocene. Tricart (1961, p. 142) notes that mountainous valley streams have essentially three sets of alluvial landforms; the major season channel of regularly reworked alluvial gravels, a major channel and associated vegetated bottomland reworked perhaps every 30–50 years, and higher surfaces, levées, and valley walls modified by only rare truly catastrophic events. Recent floods on the Big Thompson River in the Front Range of the Colorado River (300 mm of rainfall in 13 hours, estimated peak discharge 883 m$^3$/s from about 155 km$^2$, estimated recurrence interval 500 years) abraded canyon walls and completely reworked valley bottom deposits (U.S. Geological Survey (1977)). Coffee Creek in the Trinity Mountains, California, reworked glacial and other alluvial deposits during a rare flood altering all of the valley bottom topography (Stewart and LaMarche (1967), see also Helley and LaMarche (1973)).

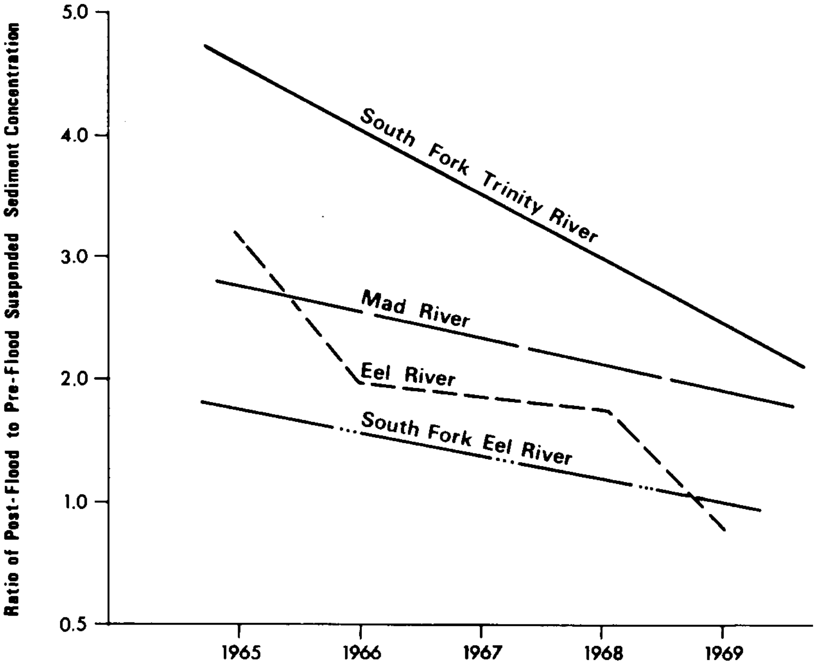

Figure 6. Recovery or decline in sediment yield after major floods of 50–100 year recurrence intervals, Northern California (Anderson (1970))

These major flood events all perform work in moving quantities of debris and particles which exceed the competence of any smaller events. Thus some kinds of work are performed and specific features such as boulder levées created which cannot be reworked or recreated during intervals between these very rare events. Because reworking of finer deposits and abrasion of bedrock do continue, specific features of the landscape must be related to specific events as Tricart (1961) suggests. In general, such catastrophic floods appear to require high relief as well as torrential rainfall, sometimes coupled with snowmelt.

In such cases non-recovery is related to a threshold of competence attained only during the event of highest magnitude. Non-recovery, as demonstrated earlier, may also result from inactivity or the inability of vegetation and average flows to reconstruct riverine topography in arid regions. As in mountainous terrain, several distinctive alluvial landforms related to different flow regimes may exist (Hedman (1970), Hedman *et al.* (1972)) although firm conclusions regarding the precise origin of each of these alluvial landforms cannot be drawn on the basis of present information.

## HILLSLOPES

Climate determines both the relative importance and the magnitude of various hillslope processes. Assuming similar lithostructural conditions, in arid and semi-arid environments the main hillslopes process is rainwash, while in humid regions, both temperate and tropical, chemical weathering and removal by solution, creep and sliding predominate. If landform conditions are not similar, however, processes and their resultants may differ markedly under the same climatic regime. As in river systems, thresholds of different processes vary with gradient, slope length, and cover. Despite these variations, some generalizations may be made about the concept of recovery and its importance in evaluating the significance of high magnitude events on hillslopes in different climatic regions.

*Hillslope failure*

Three conditions are customarily prerequisites for sharp thresholds of hillslope failure in consolidated rocks: availability of a continuous debris mantle, steep hillslopes, and intensive rainfall (or rapid snow melting). These are most commonly found in humid montane environments. In such regions, the effectiveness of a single event—an intensive rainstorm—in changing a landform and in denuding large amounts of material, is likely to be highest. Such events shape both recoverable and irreversible landforms, such as slide or avalanche scars, which may develop into first order valleys upon gullying. Rapid mass wasting also occurs in semi-arid regions, but, as Blong and Dunkerley (1976) points out, the combination of vegetation, meteorology, and lithology which controls the rate and timing of movement may be quite complex. In arid landscapes, steeper slopes and intensive storms cannot compensate for slow rates of rock decomposition and 'wet failure' is rare except on shale and debris flows on talus slopes.

The effectiveness of these episodic climatic events in eroding hillslopes may be estimated in part by the relative denudation they produce. Available data for different climatic regions on the ratio of denudation during individual events of different return periods to mean annual denudation (Figure 7) suggests several tentative conclusions.

1. The relative denudation of a major storm in wet-tropical montane landscapes is close to the mean annual denudation, but an event of such high magnitude may recur almost every year.
2. A rare event in an arid environment may denude many times the mean annual amount of material.
3. The ratio of instantaneous to annual denudation does not vary systematically with climate. The

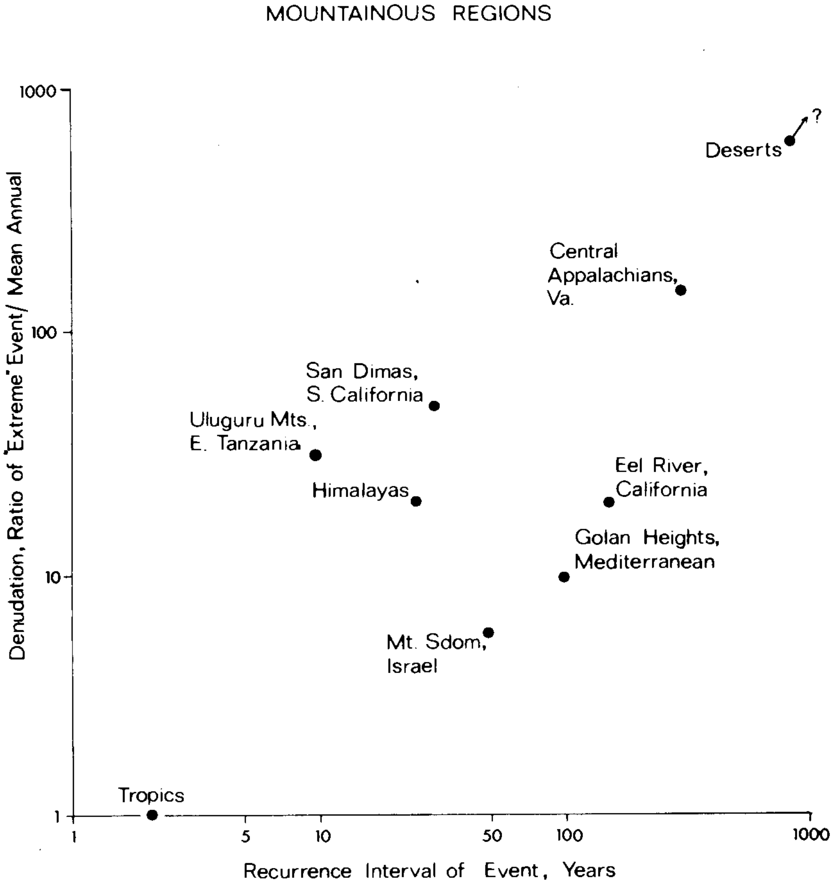

Figure 7. Relationship between denudation of hillslopes during large events of different recurrence intervals and mean annual denudation in various regions of the world (based on data from: Brown and Ritter (1971), Gerson (1972), Hack and Goodlett (1960), Inbar (1972), Temple and Rapp (1972), Rapp (1972), Rice and Foggin (1971), Simonett and Rogers (1970), Starkel (1970)

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relationships in Figure 7, however, do suggest that the absolute magnitude of denudation during a large event may not be an appropiate measure of effectiveness. Rather, just as the significance of the return period lies in part in rates of recovery processes between large events, the magnitude of the impact may be measured in part by its ratio to the mean denudation rate.

The likelihood, as noted earlier, that a force provided by a single event will be effective in denuding a hillslope varies significantly with lithology and gradient. For example, on Mt. Sdom at the Dead Sea where average annual precipitation is only 50 mm/year, the shale slopes yield large amounts of debris in each moderate event and mean annual denudation is 1·0 mm, while denudation during an exceptional storm may be as much as 10 mm. A survey of highest rainfall intensities recorded and their geomorphic effects in the Appalachian and Piedmont provinces (Costa (1973), unpublished) shows that rainstorms including intensities higher than 300 mm/day cause extensive avalanching on the long, steep Appalachian hillslopes whereas no failure occurs on shorter and more gentle Piedmont hillslopes. In Southern California 500 mm/month of rain in 1966 caused soil slippage on slopes averaging 43°, whereas the more intensive storms which occurred in 1969 (up to 900 mm/month of precipitation), triggered the same process on hillslopes averaging 39° (Rice and Foggin (1971)). Similarly, Simonett (1970) in New Guinea observed that threshold angles for different hillslope processes are mudflows—2°, rotational slumps—8°, debris slides and complex landslides—15°, debris avalanches—25–30°. As slope angle decreases, mode and rate of denudation change so that less powerful processes become predominant.

On very gentle slopes and in small catchment areas, similar processes may predominate in diverse climatic and litho-structural environments. Upper portions of hillslopes, or divide belts, often have gentle gradients and potential runoff contribution to any point is very small. At such margins weathering and removal by solution are the dominant denudational agents and the resultant features are found in very diverse climates, lithologies and structures. Hilltop depressions, for example, are common in very different environments: limestone terrains Gerson (1974)), folded metasediments under tropical, savanna climate (Brosh and Gerson (1959)), igneous and metamorphic rocks under humid temperate climate (Cleaves *et al.* (1970)), and on shale and marl under arid climates such as in the Dead Sea region (Israel) or the Painted Desert (Arizona). Hillslope angle and rainfall characteristics may be transformable in such systems. Thus, in a karst area in the Upper Galilee, Israel, receiving a mean annual precipitation of 600 mm, the maximum angle of slope for karst depression formation is 15°, whereas in a more humid area in the same region which receives 900 mm/year, the maximum angle decreases to 10°. Moving to a tropical, savanna landscape, receiving under 750–900 mm/year of mean annual precipitation and intensive thunderstorm rainfall, in a very active weathering environment on soils underlain by metasediments, this marginal gradient decreases to 7° (Brosh and Gerson (1975)).

Because of the apparent inverse relationship between precipitation magnitude and intensity and hillslope gradient required to produce rapid mass wasting, a correlation between the two across a variety of climates might be expected. However, while trends in a given location are discernible, as the authors of the papers in the recent volume (*Geografiska Annaler* (1976)) on rapid mass wasting point out, hillslope form, vegetation type, moisture regime, and stratigraphic sequence introduce too many variables to permit a simple interregional correlation.

### *Formative events and recovery*

To some degree hillslope denudation, more than sediment transport in rivers, is directly related to hillslope landforms. However, events which remove most of the denuded material need not be those which shape hillslopes or determine the location and evolution of first order valleys.

Presumably the suggested differences between the 'typical' straight hillslopes of arid regions and the convex–straight–concave hillslopes of humid regions are due to the differential processes of solution, creep, and rainwash noted above (Frye (1959)). However, comparative studies of hillslope processes and forms have shown that the same forms may be generated by very different combinations of structure, lithology, and processes acting over varying periods of time. Hillslope scars which are potential first order channels are used here to illustrate some relationships betweeen the relative landforming effectiveness of large and rare events as opposed to intervening events of small magnitude or intensity.

Watersheds in northern Jamaica show the same morphometric characteristics as watersheds in southern portions of the mountainous eastern part of the island. Drainage density is similar on both sides. Both sides of the island experience high rainfall (greater than 3,000 mm/year). However, on the south, rain is highly seasonal (Gupta (1973)). Both the 'more arid' southern part and the north are hit by hurricane storms and trade winds cyclones while frontal systems derived from the northeast provide a third source of precipitation on the northern flank. The effective, formative, storm type appears then to be the hurricane, recurring roughly every ten years, which is both intensive and frequent over both sides of Jamaica.

In subhumid Galilee, northern Israel, the rocks are mostly massive dolomites and limestones, yet the landscape appears to be sculpted by flowing water not solution. Karst features are not predominant, and most first order valleys do not follow fracture systems. However, more than 80 per cent of the denuded material is removed by carbonate solution, transported by percolating water and discharged by springs. Here moderate to intensive rainstorms producing runoff and erosion shape the landscape, determining the siting of first-order streams and the shape of hillslope profiles. Yet the topography is being reduced by solution and percolation processes which remove most of the denuded materials but do not determine the shape of most landforms (Gerson (1974)).

Tropical Storm Agnes was the most intensive storm in recorded history in the Mid-Atlantic provinces in the United States; yet the higher intensities recorded (350 mm/day) did not trigger slope failure in the Piedmont province nor was overland flow widespread over the wooded natural hillslopes. Transport in the existing drainage net was accelerated, but new channels were not initiated. The location of small valleys over much of the Piedmont landscape may be consequent upon joint systems in the rock and weathering and solution processes play a major role in formation of the hilly topography (Bunting (1961), Cleaves *et al.* (1970)).

In contrast, the same rainfall in the Appalachian Valley and Ridge Province initiated landslides over wide areas (Costa (1973) unpublished). These and other exposed areas, however, do not seem to become part of the open channel network. Over periods of decades vegetation invades the exposed area gradually reducing the difference in relief, initially 1 to 2 m, between landslide scar and adjacent rubble levée (Mann (1974)), although evidence of their existence remains as ridges on the forest floor and alluvial fans at the junction of hillslopes and valley floor. Bogucki (1976), reviewing historical records for the southern Appalachians, suggests that intense heavy rainfalls which produce major slides in the highlands have recurrence intervals of 100 years or more. Many remain clearly visible more than two decades after initiation despite gradual recolonization by vegetation (Bogucki (1976), Mann (1974)).

Sliding on hillslopes is an important geomorphic process in many mountainous, humid regions. For example, Tanaka (1976) estimates that periodic debris avalanching occurs with roughly a 5-year frequency, and extraordinary avalanches triggered by earthquakes (see below) with recurrence intervals of 100 years. While the denudation rates of frequent slides and soil erosion on vegetated slopes are within an order of magnitude of the rates generated by the rarer events, the scarred area created by episodic events appears to be obliterated at a rate of roughly 0·038 per year (p. 161).

Recurrence intervals of hillslope forming or scar producing storms vary from region to region and within a region, depending upon many other variables. Indeed, the recurrence intervals given here are regional and do not imply that a specific event reoccurs on precisely the same patch of ground. The probability that this will occur is considerably less than that a comparable event will recur within the area. In the examples given in Table I recurrence intervals of threshold or formative events range from 5 (Japan) to more than 100 years (Southern Appalachians). In wet-tropical and monsoon montane environments, slides are the dominant hillslope process, removing the thickening soil and non-weatherable mantle, and exposing further rock to intensive weathering and soil formation. Amphitheatre valleys in montane landscapes in Hawaii (Scott and Street (1956)) landslides in New Guinea (Simonett and Rogers (1970)) and in Hong Kong (So (1971)) are illustrative examples. Characteristic slide scars and

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Table I. Some examples of estimated recurrence intervals* of events producing mass wasting scars and recovery times

| Location | Mean annual precip. (mm) | Recurrence interval (years) | Recovery period | Reference |
|---|---|---|---|---|
| S. and C. Appalachians, U.S. | 1,000 | $\geqslant 100$ | $>25$ | Bogucki (1976)<br>Costa (1973) |
| S. Auckland, New Zealand | 1,800 | 30 (grass)<br>100? (forest) | — | Selby (1976) |
| Himalayas, India | 2,000–4,000 | 20–25 | — | Starkel (1970, 1972) |
| New Guinea | 4,000 | | 25–30 | Simonett and Rogers (1970) |
| Tanazawa Mountains, Japan | 2,000 | 5 (smaller)<br>100 (large) | $<25$ | Tanaka (1976) |
| Hong Kong | 2,169 | | | So (1971) |
| Hawaii | $>2{,}500$<br>4,800 max. | 1 (139 in 3–5 years) | 3 to 5 | Scott and Street (1976) |
| W. Andöya, Scandinavia | 1,000 | 50–60 | — | Rapp (1976) |
| Uluguru Mtns, Tanzania | 1,058 | 10 | 2–10 | Temple and Rapp (1972) |

* In area, not necessarily on same spot.

levées in periglacial regions of Scandinavia (Rapp (1974)) and in the semi-arid White Mountains in California (Beaty (1974)) all owe their origin to intermittent events.

Recovery processes and periods are less well documented (Table I). On a very small scale Schumm (1956) described an annual recurring process of rill formation by minor incision of rainwash and eradication of the rills by creep during winter months on hillslopes at Perth Amboy, New Jersey. As in river channels, etching and planation of the surfaces of hillslopes may occur on time scales varying from months to millenia (see Bryan (1940)). The process appears to be relatively rapid in wet-tropical regions (Wentworth (1943)) and may take 25–60 years or more even in fast-healing landscapes such as the mountains of New Guinea (Simonett and Rogers (1970)). As noted above, in the humid temperate region slides on hillslopes and first order valleys of an upper Shenandoah watershed remained fresh decades after formation. Some swales on hillslopes in the arid southwestern United States show little or no change after ninety years (Trefethen (1976, p. 34)). Still larger time spans are characteristic of debris flows generated by highly intensive rainstorms on talus slopes of arid regions such as the Sinai Peninsula, where this type of process is the main agent to move coarse gravel from the upper scarps to the foot of the talus.

While the emphasis in this paper is upon climatic events, it is interesting to note that seismic activity in tectonically unstable regions can also trigger failures on steep debris covered slopes in the tropics (Tanaka (1976) above). Simonett and Rogers (1970) report that in mountainous New Guinea the average rate of denudation is 0·70 mm/year, excluding the direct effects of earthquakes and 1·20 mm/year, including intensive earthquake effects. Pain (1972) indicates that 25 per cent of an area of 240 km$^2$ in Papua, New Guinea, was directly affected by slope avalanches during and following the 1 November, 1970, earthquake. Mean hillslope denudation was 0·11 m/event, but the areas specifically affected lost four times that amount. Under these conditions climatic effects cannot be distinguished from tectonic or seismic ones as generators of mass movements. To the extent, however, that specific climatic and tectonic events are separable in time, tectonic disturbances simply increase the frequency of 'high-magnitude' events in hillslope sculpture and denudation. The frequency of formative events appears to be high in both periglacial and humid tropical regions and low in temperate or truly arid regions. The spectacularly large and rare event in the wet montane tropics, while large, is part of a continuum of hillslope processes removing the rapidly weathering mantle. In contrast, in arid areas weathering limited slopes may be denuded and shaped by relatively frequent events. Effectiveness of the latter is controlled less by absolute magnitude than by the absence of recovery. Events are of large magnitude, but of common occurrence.

The examples cited here of hillslope denudation and alterations of hillslope form suggest that events casually termed 'catastrophic' may in fact be normal or common in many environments. The relative importance of individual events, however, cannot be measured solely in terms of recurrence interval or magnitude of denudation or erosion. On hillslopes, as in channels, both time and magnitude have significance only in terms of the continuous processes typical of a given climatic region. The intensity of precipitation may be the same in a tropical and in an arid region, but both the rarity and the impact of a rainfall of high intensity will clearly be vastly different. In arid regions and in small drainage basins denudation in solution or as clastic material follows roughly similar patterns with clastic transport and higher flows proportionately more important than in humid regions or large drainage basins.

For many landforms a relative scale measuring the significance of erosion or deposition by high magnitude events appears to be associated with a relative time scale related to climate and vegetation which influence the rate at which recovery of specific forms takes place following changes produced by a large event. Relative scales expressing both magnitudes of force and durations of time, as used illustratively in this paper, could be constructed to characterize a range of climates, landforms, and time. These, of course, are broad generalizations. Even the use of mean annual, as opposed to seasonal sediment load, requires further inquiry (see Wilson (1973)). More important, at present available data on recovery times following major events on rivers and hillslopes are not sufficient to permit us to make a preliminary quantitative generalization. Information is beginning to accumulate on the geomorphic effects of large events in diverse regions, and on the much less dramatic process of recovery which may permit such generalization.

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