RAINFALL AND FLOODS. HYDROLOGIC STUDIES

Francisco Nunes Correia
Laboratório Nacional de Engenharia Civil
Instituto Superior Técnico

Summary

Engineering geologists and other professionals concerned with the study and prevention of landslides and other mass movements need to have a clear idea of the basic concepts of geomorphology and landform evolution. Fluvial geomorphology is an important subtopic of this scientific field. Rainfall and floods play an important role in the evolution of fluvial forms. Therefore, they are important agents of the geomorphology evolution. In this paper an attempt is made to present some basic ideas and concepts of fluvial geomorphology, giving special attention to the role played by floods. The river basin is presented as a geomorphologic unit and the river and river basin dynamics are introduced. In this context, the role of floods as geomorphologic agents is emphasized. Finally, the concepts of time scales in geomorphology, geomorphologic thresholds, and complex response, introduced by other authors, are briefly presented.

1. Introduction

A question can be asked: Is it important to address the topics of floods, storms and hydrologic studies in a course dedicated to natural hazards and engineering geology?

The answer is yes. In fact, a large part of the surface of the earth is composed of fluvial systems of all sizes. The evolution and the dynamics of these systems, the relationship and close interlinkage among geologic structures, soil movements and hydrologic variables need to be understood.

The hydrologic cycle plays a very relevant role in fluvial geomorphology and landform evolution. This is particularly true for extreme events, namely floods and storms, that have a crucial role as geomorphologic agents.

Engineers and other professionals interacting with landforms and its evolution, need to be aware of these factors and to understand its intrinsic dynamics. Geomorphology and fluvial geomorphology provide important tools for this awareness.

In this paper, some basic concepts relevant for the understanding of river and river basin evolution are presented. It should be noted that this is not a report presented by a geomorphologist. On the contrary, it is an attempt done by a hydrologist. The purpose is to draw a broad picture of some relevant topics concerning river morphology and dynamics and not to treat in depth these subjects. The presentation is largely based on figures and charts displayed in the appendix and taken from literature quoted in the references section.

2. The River Basin as a Geomorphologic Unit

It is important to look at the river basin as a geomorphologic unit and to understand the intricate relationship among all variables and factors.

According to a classic decomposition of the fluvial system three zones can be considered, as presented in Figure 1. The production zone, the transfer zone and the deposition zone. The production zone is basically the drainage basin where most river flow and sediment are generated. The transfer zone is formed principally by the channels of the river and main tributaries, conveying water and sediment from the basin to deposition areas. Finally, the deposition zone is the estuary or delta, or simply the alluvial fan where reception and deposition are the main processes. This decomposition is somewhat artificial in nature and its purpose is to emphasize the various processes prevailing in different portions of the fluvial system.

Several variables and controls are responsible for shaping the overall behaviour of the watershed. These variables are presented in Table 1 and it can be immediately seen how important the climatic and hydrologic aspects are, together with geologic and geomorphologic factors and land cover and land use practices. Land use practices deserve a special reference. In fact, the type of soil cover may have a very significant impact in the response of the watershed, namely causing changes in infiltration rates, as it can be see in Figures 2 and 3. This is important in the evolution of streams and their drainage basins as it has been acknowledged, at least, since an important paper presented by Horton in 1945 (3).

3. River and River Basin Dynamics

Rivers are dynamic in nature. This is particularly true in alluvional channels. Even steady fluvial forms correspond to a dynamic stability and not to a static condition. It is interesting to mention the large diversity of shapes that alluvial streams can take, corresponding to different stages of its evolution. These forms are displayed in Figure 4. The evolution of river and river basin geomorphology can be only understood as the interaction among several variables. Many attempts to quantify these interactions as a key to understand fluvial dynamics have been made. A few examples will be quoted from the literature.

On Figure 5 the effect of average temperature on the relation between mean annual runoff and mean annual precipitation is displayed. It can be noticed that a mean annual precipitation of 50 inches can produce from about 10 to 30 inches of runoff when the mean annual temperature decreases from 70°F to 40°F. Mean annual runoff is a crucial factor in geomorphology evolution, with a very important role in the erosion process.

The relationship between runoff and sediment yield is displayed on Figure 6. It can be seen that this is not a linear process. In fact, a maximum of sediment yield is attained for an effective precipitation between 10 and 20 inches and attenuates outside this range. This behaviour is explained by the role played by vegetation. Below 10 inches of effective precipitation the soil is uncovered but the erosional capacity of rainfall is small. Above 20 inches rainfall may have significant erosional capacity but vegetation develops and protects the soil from erosion. Between 10 and 20 inches the soil is still rather unprotected and the precipitation is already rather erosive.

These relationships are related to the overall behaviour of the river basin. A few relations related to the stream channel variables can also be presented and are specially important for engineering purposes.

Many experiments have shown a close interaction between channel slope, sediment load and channel shape. Figure 7 displays the relationship between slope and sinuosity for a given discharge and Figure 8 presents the relationship between channel slope and sediment load, and the association of of these two factors with the shape of the channel.

The close relationship between sediment transport and water discharge is well expressed by the qualitative geomorphologic relation, presented by Lane in 1955 (5):

$$Q_s . d \approx Q . S$$

Q_s - Bed material load
d - Median sediment size
Q - Mean water discharge
S - Channel slope

Many attempts have been made to express this classic relationship in more quantitative terms. An example, extracted from a recent book authored by Chang (6), is presented in Figure 9.

The merit of the Lane's expression, however, is precisely its qualitative and general formulation. It provides a very important tool for understanding the behaviour and the evolution of a river when subject to changes in any of its basic components. Therefore, it is a very important instrument for river engineers.

Figure 10 provides a very interesting representation of the Lane's qualitative equation and it is obvious its application to predict the evolution of rivers subject to changes in any of the terms. Table 2 provides a systematic qualitative description of channel metamorphosis largely based of Lane's approach.

Finally, it is interesting to present some of the characteristic patterns of geomorphologic response to disruption. These patterns are displayed on Figures 11 and 12. The concepts of reaction time and relaxation, time are introduced and the complex interactions of precipitation, vegetation and geomorphologic response under changing conditions are displayed.

4. Floods as Geomorphologic Agents

Floods play a crucial role as geomorphologic agents. Its impact can be considered in the three zones of the fluvial system, namely, the hillslopes, the stream channels and the floodplains.

Two different types of flood events must be considered, as noted by Ward (7). Flood events with relatively low magnitude but occurring frequently, say every five or ten years, and flood events with high magnitude but occurring rarely, like every hundred or thousand years. The first type of events is responsible for shaping the main characteristics of the river channel under rather steady conditions,. The second type of floods is an important cause of disruption leading to new stages and new forms of equilibrium and playing an important role in building the floodplain.

Naturally, the impact of a flood event does not depend only from the magnitude of the flood, but also from the stability of the river channel or the floodplain.

The impact of flood events on hillslopes is basically related to higher erosion rates and the effects of water running below the surface (interflow, pipeflow). Flood hazards are frequently associated with landslides and slope failure. These phenomena are geomorphologic agents and are also responsible for a significant increase in sediment load.

The impact of flood events on stream channels is basically related to an acceleration of sediment transport processes, an increase of erosion and transport capacity, the aggradation or degradation of river beds and changes in meandering patterns.

As it was stated before, low magnitude but frequent floods play a very important role in the formation of the stream channel. It is generally accepted that the stream channel accommodates roughly the mean annual flood. Based on this idea, many relationships between characteristic discharge and stream channel dimensions have been established. An example of these studies are the expressions derived by Bray (8). From 70 gravel-fed streams in Alberta:

$$B = 2.380\ Q_2^{0.527}$$

$$D = 0.266\ Q_2^{0.333}$$

where B and D are average water surface width and depth, respectively, in feet, and Q_2 is the 2-year flood.

Not only width and depth of the river channel are related to discharge, but also sinuosity. Dury (9) established the following relationship between the wavelength in feet, λ, and the mean annual flood in cubic feet per second, Q_{ma}:

$$\lambda = 30\ Q_{ma}^{0.5}$$

the relationship is displayed on Figure. 13. This result can be largely improved if information on type of sediment load, namely percent of silt-clay, M, is included:

$$\lambda = 1890 \frac{Q_m^{0,34}}{M^{0,74}}$$

or

$$\lambda = \frac{Q_{ma}^{0.48}}{M^{0.74}}$$

Q_m is the mean annual discharge.

The impact of flood events on floodplains is basically related to the formation and evolution of this plain. High magnitude and rare floods are the main agent of this process. As flood waters overtop channel banks and spread out, their ability to transport material in suspension is reduced and the coarsest material is dropped near the edge of the channel, while finer material is transported farther. Flood plain can be regarded as a storage or sediment across which channel flow takes place.

5. Main Concepts in Fluvial Geomorphology

Three basic concepts, introduced or elaborated by Schumm (1), are extremely important for understanding the role of flood events as fluvial geomorphologic agents. It is adequate to present briefly these tools, namely the concept of time scale in geomorphology, the concept of geomorphologic threshold and the concept of complex response.

a) Time scale

Landform evolution can be considered in three time spans of different duration: cyclic, graded and steady. This is illustrated on Figure 14 taken from Schumm (1).

Cyclic time scale, corresponding to several millions of years, encompasses a major period of geologic time. During this time span the characteristics of a fluvial system change progressively, attaining some sort of dynamic equilibrium.

Graded time scale refers to time spans of a few hundreds or thousand years, in which there is a continuous adjustment of the components of the fluvial system. Variations around mean characteristics are seen as fluctuations around a steady-state equilibrium.

Steady time scale corresponds to a possible static equilibrium or quasi-static situation. In this time span, going from a few days to a few years, geomorphologic characteristics appear to be time independent.

The relationship among fluvial characteristics and their independent or dependent nature change with the time scale being considered. This is displayed on Table 3.

b) Geomorphologic thresholds

According to Schumm(1), some discontinuities in the erosional and depositional record may be the result of the exceeding of erosional thresholds,which are the stage at which an effect is produced.In fact, changes in fluvial erosion and deposition should not always be attributed to external influences such as climate, tectonics and base level changes. They may be caused by the rupture of an intrinsic condition of incipient stability built in time without a change of external influences.

Flood events may act as one of the most important agents causing the rupture of geomorphologic thresholds. This is clearly shown in Figures 15 and 16.

c) Complex response.

In a fluvial system one event can cause a complex response as the components of the system respond to change. The complex response of a fluvial system to change is a type of complexity that is inherent in the fluvial system, regardless of the complexities of the response caused by external factors.

The concept of geomorphologic thresholds and the concept of complex response make the explanation of many erosional and depositional changes in fluvial systems possible, without the need for appealing always to external factors.

Complex response is very well illustrated by an experiment described by Schumm (1) and displayed on Figure 17. In graph A and B incision is occurring and progressing from the mouth of the river to the upstream region. Erosion of the river bed causes rejuvenation of tributaries and large quantities of sediment loads are conveyed by the main channel. This sediment load is transported to the lower reaches and the deposition and formation of a braided stream becomes inevitable (graph C). As tributaries become adjusted, sediment yield coming from upstream decreases significantly,causing incision to start again and a new phase of channel erosion to occur, as it is presented in graph D. The complex evolution of fluvial processes is not caused by external controls, like base level changes, but simply by the intrinsic nature of the fluvial system. Flood events may play a crucial role in triggering this kind of complex response by starting a period of incision and rejuvenation.

6. Summary and Conclusions

Most of the surface of the earth is composed of fluvial systems. Therefore, fluvial geomorphology is essential to understand landform evolution.

River basins should be seen as geomorphologic units and the dynamic characteristics of rivers and river basins should be understood as a whole.

Flood events and other hydrologic factors play a very important role as geomorphologic agents.

The concepts of time scale, geomorphologic threshold and complex response, are very important tools for a complete understanding of the dynamics of river basins and the role of hydrologic factors in its evolution process.

The study of fluvial processes and its relationship with hydrologic characteristics of the river basin, is relevant and has practical importance for geologists, geomorphologists, engineering geologists, civil engineers, lands use planners and environmentalists.

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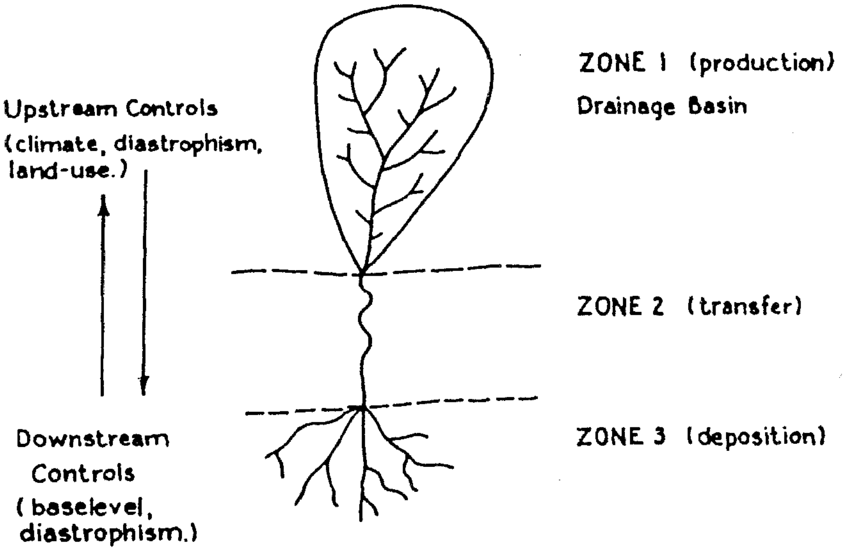


Fig.1 -The three zones of the fluvial System (from Schumm(1)).

Table 1-Fluvial system variables (from Schumm (1)).

Drainage system variables
1. Time
2. Initial relief
3. Geology (lithology, structure)
4. Climate
5. Vegetation (type and density)
6. Relief or volume of system above baselevel
7. Hydrology (runoff and sediment yield per unit area within Zone 1)
8. Drainage network morphology
9. Hillslope morphology
10. Hydrology (discharge of water and sediment to Zones 2 and 3)
11. Channel and valley morphology and sediment characteristics (Zone 2)
12. Depositional system morphology and sediment characteristics (Zone 3)

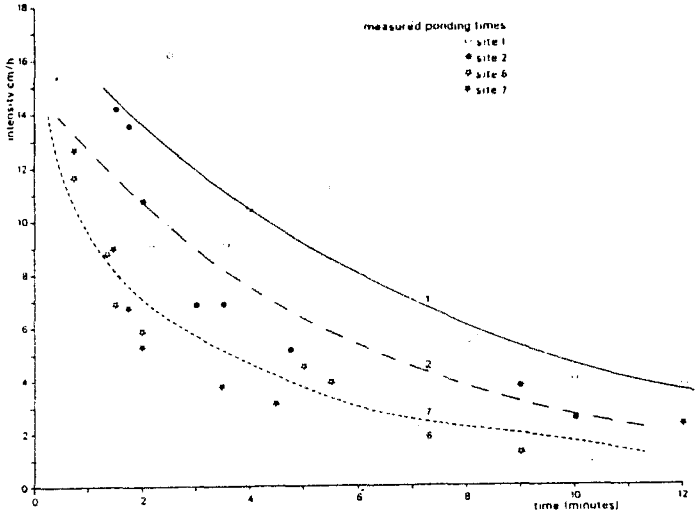


Fig. 2 -Infiltration envelopes for erodible soils from Northern Morocco. Site 1 - red Mediterranean soil recently cultivated. Site 7 -Similar soil with a surface crust. Site 2 - Non-crusted regosol. Site 6 - Crusted regosol (from Imeson (2)).

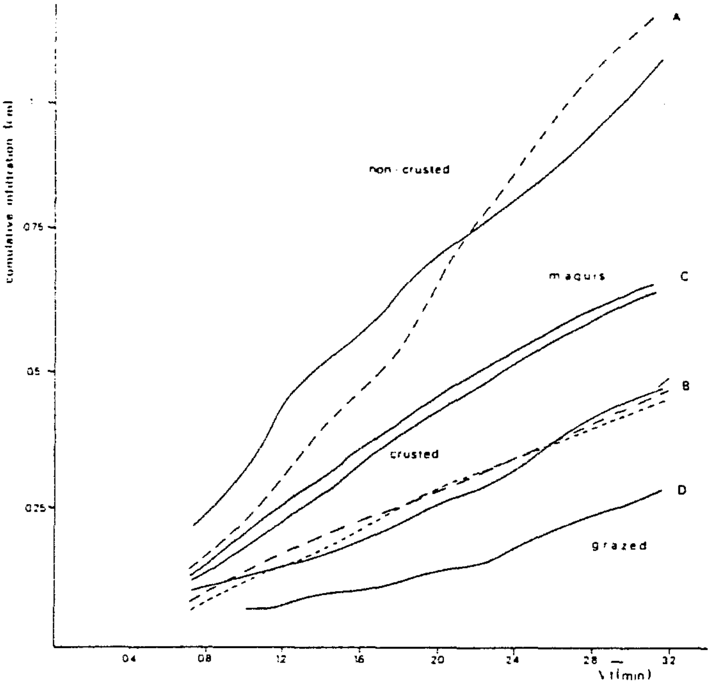
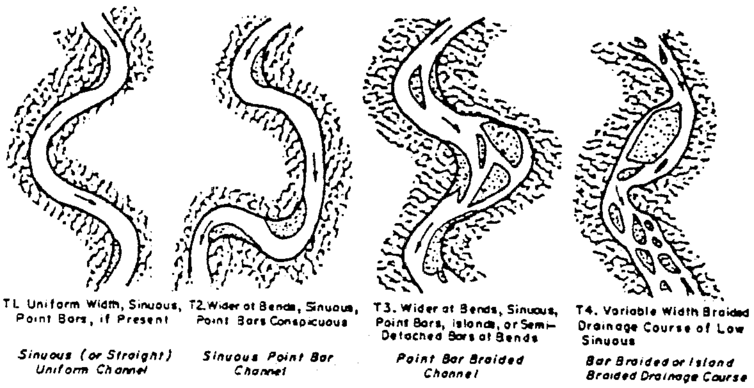
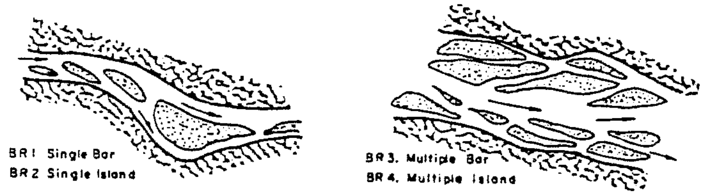


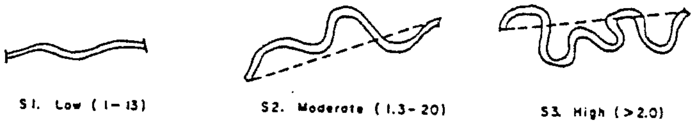
Fig. 3 -Cumulative infiltration rates measures with a rainfall simulator in Northern Morocco. A - cultivated non-crusted Mediterranean soil. B-Same soil with crust. C-Maquis. D-Red soil grazed and trappled by goats and sheep (from Imeson (2)).



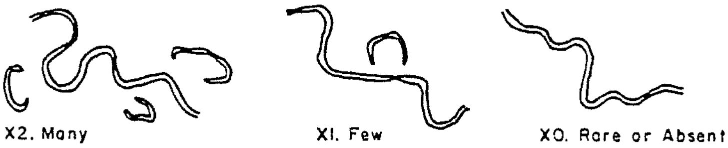
(a) Variability of Unvegetated Channel Width: Channel Pattern at Normal Discharge



(b) Braiding Patterns



(c) Types of Sinuosities



(d) Oxbow Lakes on Floodplain

Fig.4 -Large diversity of river morphology (from Simons and Senturk (4)).

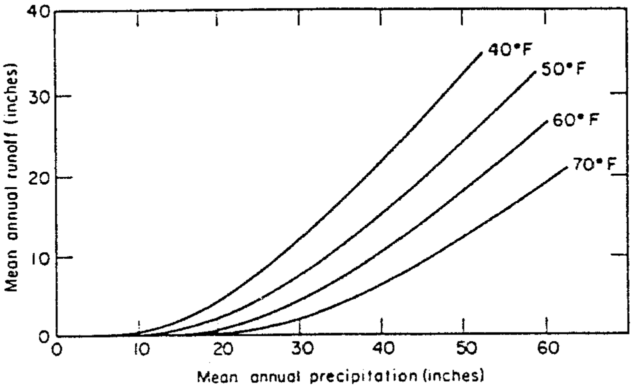


Fig.5 -Effect of average temperature on the relation between mean annual runoff and mean annual precipitation (from Schumm (1)).

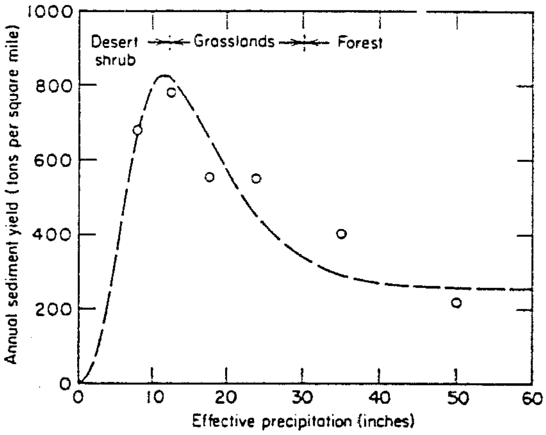


Fig.6 -Variation of sediment yield with climate, as based on data from small watersheds (from Schumm (1)).

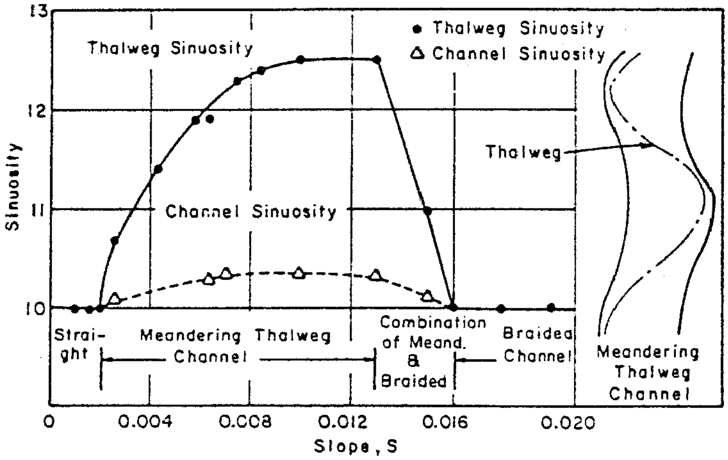


Fig.7 -Sinuosity versus slope for a constant discharge of 0.15 c.f.s. (from Simons and Senturk (4)).

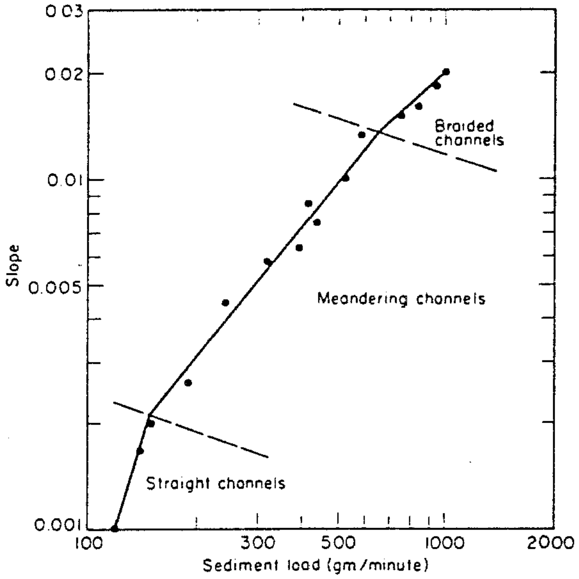


Fig. 8 -Relation between sediment load and flume slope showing increased rate of sediment transport at thresholds of pattern change (from Schumm 1977 (1)).

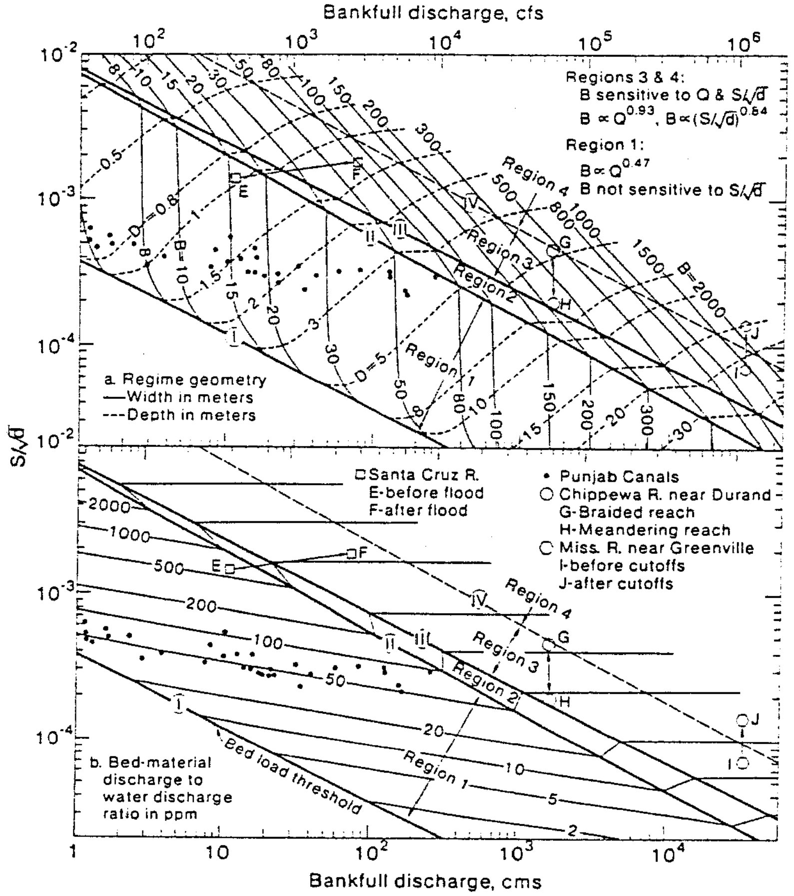


Fig. 9 -Regime relationships of sand-bed rivers. S-Slope, d-Median particle size (from Chang (6)).

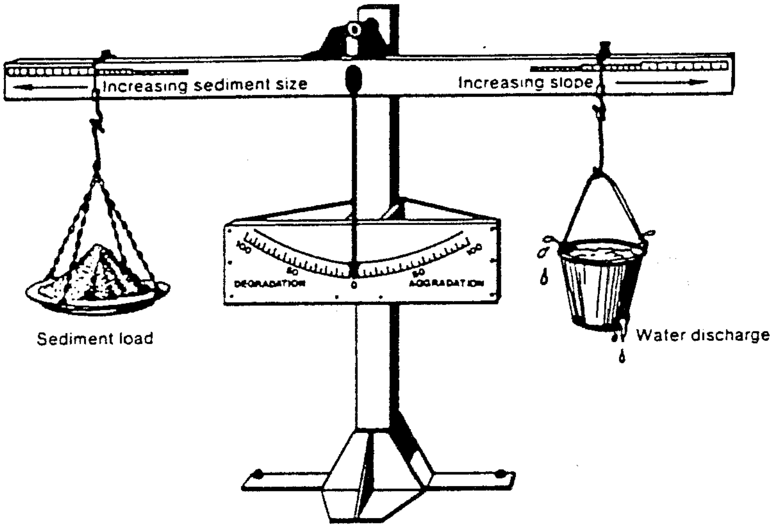


Fig. 10 -Representation of Lane's qualitative relationship for channel balance (from Chang (6)).

Table 2-Qualitative model of channel metamorphosis. F-Width/depth ratio, P-Sinuosity, λ-Wave length, B-Surface width, D-Depth (from Chang (6)).

Increase in discharge alone:

$Q^{+} \sim B^{+}D^{+}F^{+}\lambda^{+}S^{-}$

Decrease in discharge alone:

$Q^{-} \sim B^{-}D^{-}F^{-}\lambda^{-}S^{+}$

Increase in bed-material discharge:

$Q_s^{+} \sim B^{+}D^{-}F^{+}\lambda^{+}S^{+}P^{-}$

Decrease in bed-material discharge:

$Q_s^{-} \sim B^{-}D^{+}F^{-}\lambda^{-}S^{-}P^{+}$

Discharge and bed material discharge increase together; for example, during urban construction, or during early stages of afforestation:

$$Q^{+}Q_s^{+} \sim B^{+}D^{\pm}F^{+}\lambda^{+}S^{\pm}P^{-}$$

Discharge and bed-material discharge decrease together; for example, downstream from a reservoir:

$$Q^{-}Q_s^{-} \sim B^{-}D^{\pm}F^{-}\lambda^{-}S^{\pm}P^{+}$$

Discharge increases as bed-material discharge decreases; for example, increasing humidity in an initially subhumid zone:

$$Q^{+}Q_s^{-} \sim B^{\pm}D^{+}F^{\pm}\lambda^{\pm}S^{-}P^{+}$$

Discharge decreases as bed-material discharge increases; for example, increased water use combined with land-use pressure:

$$Q^{-}Q_s^{+} \sim B^{\pm}D^{-}F^{+}\lambda^{\pm}S^{+}P^{-}$$

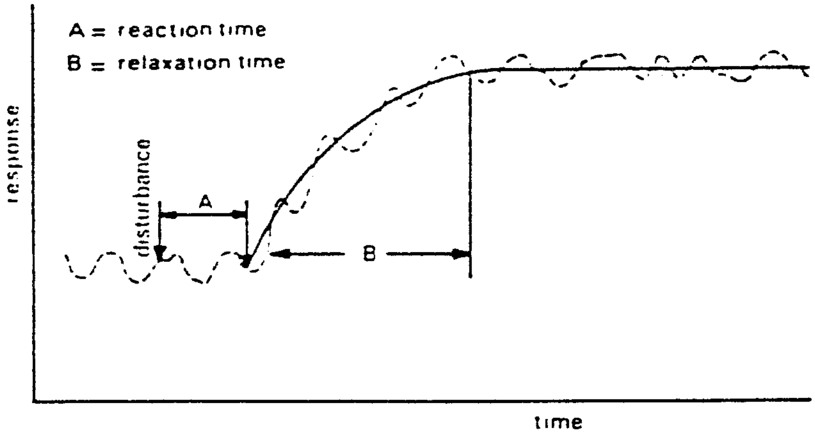


Fig. 11 -Response of a geomorphologic system subject to disruption (from Imeson 1984 (2)).

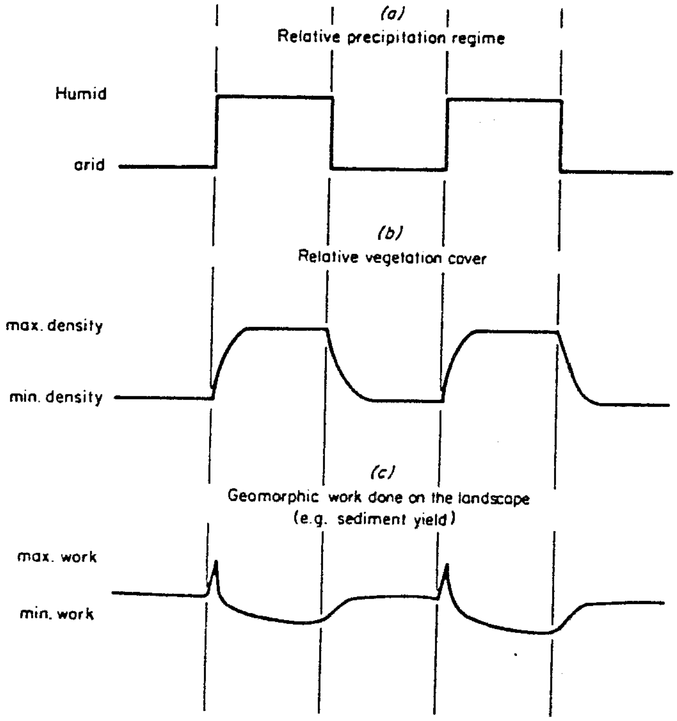


Fig. 12 -Vegetational and geomorphologic response to abrupt climate change (from Schumm (1)).

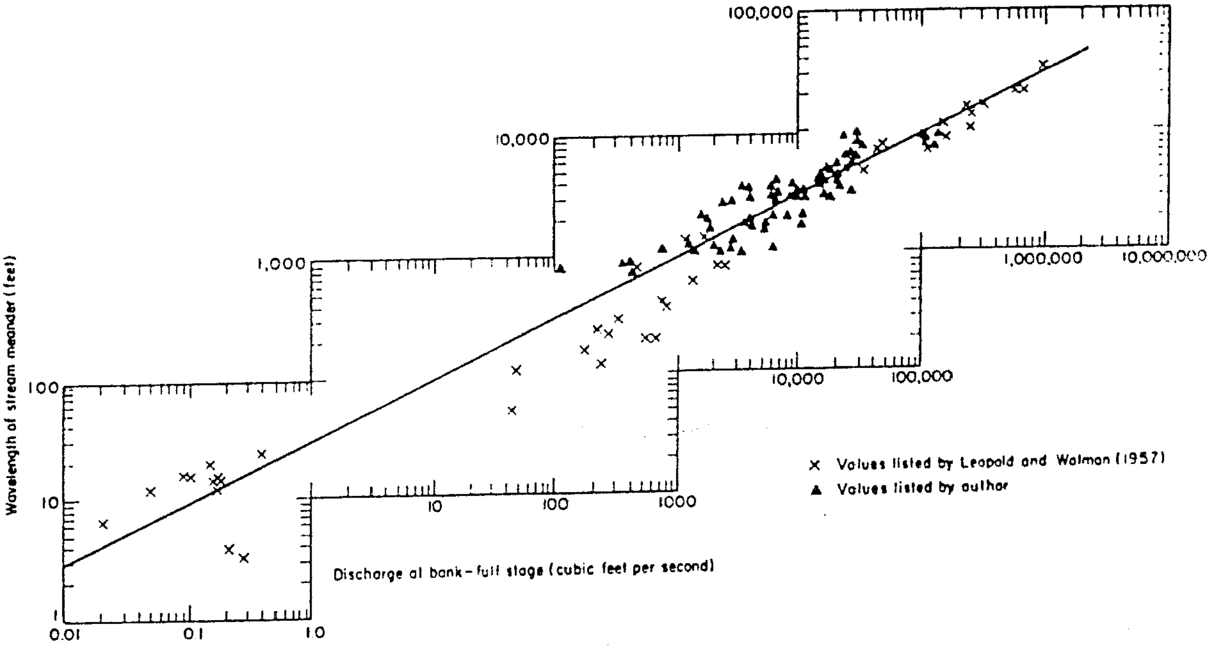


Fig.13 -Relationship Between Meander Wavelength and Bankfull Discharge (from Schumm (1)).

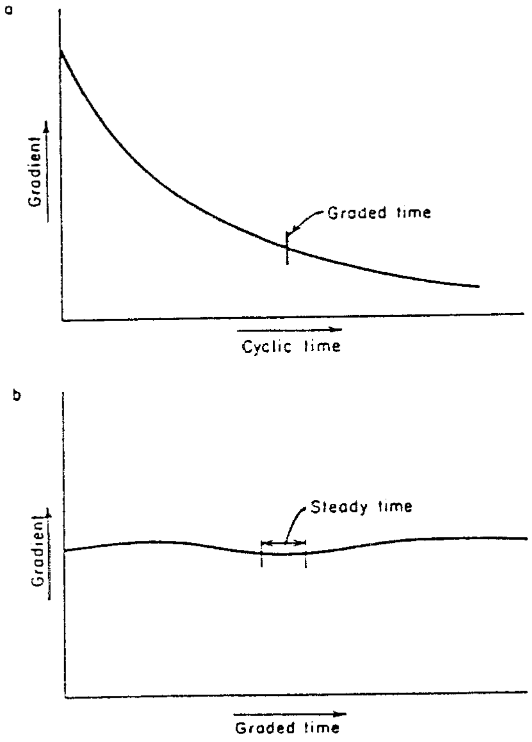


Fig.14 -Cyclic, graded and steady time spans as reflected in changes of stream gradient through time (from Schumm(1)).

Table 3-River variables for different time spans(from Chang(6)).

Variable	Status of Variable*		
	Steady (Short-Term)	Graded (Long-Term)	Geologic (Very Long-Term)
Geology (lithology, structure)	I	I	I
Paleoclimate	I	I	I
Paleohydrology	I	I	D
Valley slope, width, and depth	I	I	D
Climate	I	I	X
Vegetation (type and density)	I	I	X
Mean water discharge	I	I	X
Mean sediment inflow rate	I	I	X
Channel morphology	I	D	X
Observed discharge and load	D	X	X
Hydraulics of flow	D	X	X

*I, independent variable; D, dependent variable; X, indeterminate.

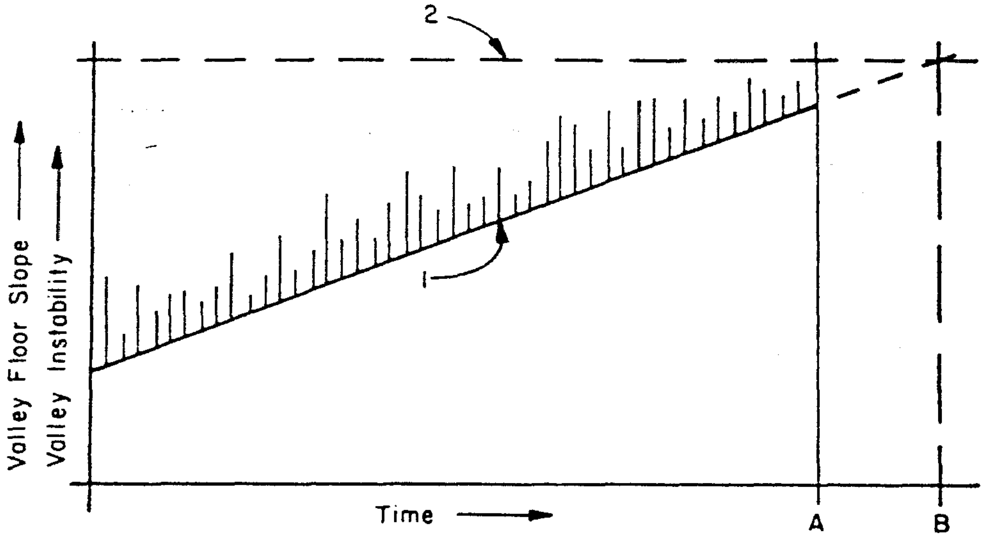


Fig. 15 -Changing valley-floor stability through time. Line 1 shows increasing instability of valley floor as it approaches failure threshold represented by line (from Schumm (1)).

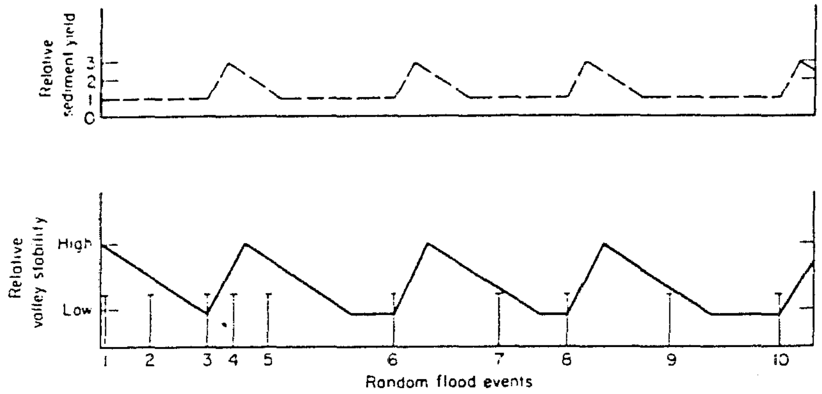


Fig.16 -Ten randomly spaced flood events (vertical lines) of large magnitude when they coincide with a period of low stability of valley alluvium (solid line), they cause incision and removal of accumulated sediment. High sediment yields (upper dashed line) are characteristic of short periods when accumulated alluvium is flushed from the system (from Schumm (1)).

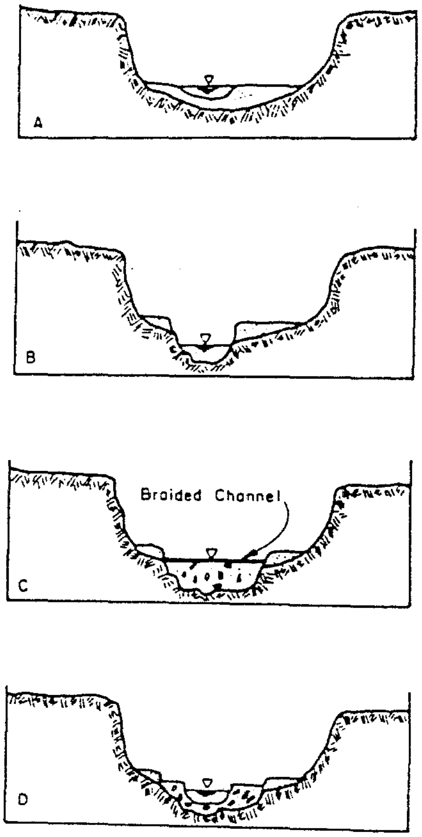


Fig.17 -Complex response of an experimental drainage basin (from Schumm(1)).