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ABSTRACT

AN EXPERIMENTAL STUDY OF BASIN EVOLUTION AND ITS HYDROLOGIC IMPLICATIONS

An experimental study was undertaken to document the evolution of a drainage basin and to identify hydrologic changes. A 9 by 15 m facility was built and filled with a homogeneous mixture of sand, silt, and clay. The material provided sufficient resistance to erosion to maintain channels and to allow valley side-walls to develop. A sprinkling system was established along the sides of the container, and it provided four intensities of rainfall to the nearly 140m^2 drainage basin. Two experiments were performed each of which documented the evolution of the drainage system on an initial flat, gently sloping surface.

The initial conditions (relief and initial surface slope) of each experiment were different, and these initiated differences in the mode of network growth. In the first experiment the network grew headward developing fully as it extended into the basin. This is termed "headward growth." In the second experiment an initial skeletal network blocked out much of the watershed, and later internal growth and rearrangement of channels occurred. This is termed "Hortonian" growth.

Both experiments evolved through the sequence of network initiation, extension of the network to maximum extension, and, finally, to abstraction. These classes of growth identify periods of time during which the major processes of drainage net development in the basin are different. Evolution can be summarized by a plot of drainage density through time which shows an increase to a maximum at maximum extension followed by a decline during abstraction. Differences in the drainage density are noted at initiation and maximum extension which reflect the differences in the mode of growth. The network following Hortonian-type growth showed a lower drainage density at maximum extension than the network which followed headward growth. The "blocking out" of the network in Hortonian growth alters sub-basin areas sufficiently to change competition among streams and subsequent channel development.

Sediment yields from the basin undergoing erosional evolution show an exponential decline with time. This overall trend is characterized by high variability. In the field the long term variability would be compounded by changes in climate and land use. Periods of high variability appear related to periods of high sediment production in the basin. Alluvial material is periodically stored and flushed in the main channel aggravating sediment yield variability. Apparently baselevel change produces degradation, which leads to aggradation in the main channel, as sediment production upstream continues. This phenomenon is termed the complex response of the basin.

Hydrographs generated on various geomorphic surfaces as evolution progressed suggest that runoff produced by lower precipitation intensities is most influenced by the geomorphology of the basin. The ratio of peak discharge to the equilibrium discharge shows a dramatic increase during the early basin development. Peak sediment yields, obtained during the generation of the one minute duration input hydrographs, show a very strong dependence on the amount of water delivered to the outlet, and follows the same relation as the peak discharge/equilibrium discharge ratio.

Lag time of the instantaneous unit hydrograph (IUH) was used as an index of nonlinearity of the hydrologic system The basin produced an increasingly nonlinear response as drainage density decreased. This may result from greater overland flow as drainage density decreases.

The efficiency of the hydrologic response, as indexed by the peak of the IUH, appears to increase to a maximum as drainage density and/or relief increases. Further increases in drainage density do not increase the efficiency of the hydrologic system.

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Chapter I

INTRODUCTION

Throughout the history of geomorphology, the changing form of the landscape with time has been a primary consideration. However, due to the short time available to the investigator, models of landscape evolution have depended largely on deductions based upon measurements of erosion in restricted areas of rapid erosion (Schumm, 1956), or on a series of landform measurements which are placed in an assumed erosional sequence (Koons, 1955; Carter and Chorley, 1961; Ruhe, 1950; Hack, 1965). These two techniques have not yielded sufficient data on the rates and the nature of geomorphic changes through time to prevent development of divergent opinions concerning the origin and development of landforms (Hack, 1960; Chorley, 1962; Schumm and Lichty, 1965). Further, this deficiency of knowledge on the character of change of geomorphic variables with time has hindered the development of basin or channel network simulation models. The models have relied almost totally on assumed and fixed probabilities for branching and growth because of the lack of information as to what these probabilities should be. Therefore, computer simulation models cannot simulate responses of the stream network to external influences such as changes in baselevel, climate or even to differences in basin lithology. A model that can include these variables would do much to better the understanding of the mechanics of network changes induced naturally by man's modifications of the environment.

In addition, efforts to predict the hydrologic character of drainage basins are handicapped by a lack of information on the effects of landform morphology on runoff, sediment yield and flood characteristics. It has been demonstrated that runoff (Carlston, 1963; Morisawa, 1962; Gray, 1961) and sediment yield (Anderson, 1954; Glymph, 1955; Hadley and Schumm, 1961) are related to geomorphic characteristics for a limited range of landforms. However, such studies must rely on comparing hydrologic and sediment yield differences among different basins. Therefore, the field situation does not allow the examination of the effects of particular variables by holding others constant. As a result, field studies rely heavily on multivariate techniques which may or may not identify the most significant variables that control differences in the sediment or hydrologic output of watersheds. Relations between the basin hydrologic response and basin configuration must also change through time as the system evolves, but little quantitative information on these changes is available. Obviously, this type of field research has been impossible during one lifetime.

Objectives

Geomorphic and hydrologic problems, such as those outlined above, are difficult to solve by field studies alone. However, experimental studies, if properly designed, may help to answer basic questions of drainage basin evolution, and this study was initiated to confront basic geomorphic questions using an experimental approach. The objectives of this research are as follows:

1. to describe the overall evolution of the drainage system from initial network growth to the final stages of network development and to describe morphologic changes within a network as the stream pattern evolved,

2. to compare the morphology of networks generated with different initial slopes and relief but with the same homogeneous material and watershed area,

3. to identify sediment characteristics of the basin as evolution of the system progresses,

4. to relate changes in the hydrologic character of the watershed to observed changes in the geomorphology of the basin of various stages of basin evolution.

The first two objectives deal with the description of network itself. The final two objectives bring together geomorphic and hydrologic data to demonstrate the influence of geomorphology on sediment yields and surface water hydrology.

Experimental Geomorphology

Experimental geomorphology is defined as the use of equipment or procedures to alter dimensions in either time or space for the purpose of identifying processes or observing morphologic changes. Such a definition includes both experiments in a laboratory and procedures which modify time or space in the field (e.g., Emmett, 1970). Inherent in the definition of a model is the process of simplification of the complex original system. The reason most models are produced is that the original system is too complex to comprehend.

To simplify a drainage system into an experimental model, one must consider the scaling ratios between the prototype and the model, the boundary conditions necessitated in the model, and the initial conditions inherent in the experimental design. Scaling ratios present problems, which have been so great, that they partially explain the lack of experimental studies of drainage basin evolution. Scaling becomes a problem because the appropriate dimensionless parameters cannot be maintained between model and prototype at a scale other than one for problems involving overland flow and erosion and sediment. Engineers have enjoyed success in model studies by identifying certain scaling ratios in simple systems. The more complex system (i.e., a watershed) in which many identified and unidentified variables are interacting has proved less amenable to dimensional analysis.

To avoid the problems of scaling ratios one may build a watershed model sufficiently large that it can be considered as a prototype. Of course, as the size of the model approaches the prototype, the advantages of abstraction are reduced. Such a tradeoff appears inevitable until suitable experimental theory exists to define scaling ratios.

In the present study the size of the basin is presumed sufficiently large to be considered a small prototype basin in which observations derived can be extended to larger watersheds in the field. Extending the observations and relations defined in a very small basin to larger natural watersheds has proven successful (Schumm, 1956). Therefore, the results from intensive observations that are possible in small basins can be applied to larger watersheds without regard to scaling ratios. Scaling, therefore, is in a temporal sense only. It is assumed that the relations derived are appropriate in a spatial sense but altered in time, that is, time is compressed by an unknown amount in relation to the field.

Experimental work frequently results in unrealistic boundary conditions. For example, flume studies must contend with rigid sidewalls of the flume and the changes in conditions produced by such a rigid boundary. In an experimental basin, as used in this study, rigid sidewalls form an unyielding boundary to the watershed, whereas in natural basins competition exists among adjoining basins. Erosion and competition along these interbasin divides allow divides to shift with time. Further, the rigid boundary produces a zone of little erosion that results in the surface near the wall maintaining its altitude through time. Nevertheless, these boundary conditions do not present serious problems in the overall experimental design. The divides of internal sub-basins do react much like natural watersheds and the observation of downwearing, capture, and competition among these sub-basins can be made.

Initial conditions also are significant. For example, one must start with a particular initial surface slope which may influence the resulting basin configuration. Initial conditions, therefore, are a long term deterministic influence on basin evolution. The identification of these deterministic components may be possible by varying the range of natural conditions and examining the resulting geomorphic configuration. Further, the range of values of particular geomorphic variables through time can be identified. The identification of the range of values that a variable can assume, particularly the minimum and maximum limits, are of importance in identifying the impact of man's modification of natural watersheds.

A. Daubree (1879) was one of the first experimentors in geomorphology. His book, "Geologie Experimentale," describes experiments involving a wide range of geologic activity including the surface expression of the Earth. Daubree realized the problems associated with experimental work, but he circumvented them by suggesting the outcome of his experiments were of primary use as a hypothesis generating device. That is, by watching landform development in an experiment, a hypothesis is generated that then can be tested in the field. This is one of the prime uses of experimental techniques in geomorphology today because there is no need to identify scaling ratios, initial conditions, or boundary conditions.

In his experiments, Daubree used analogous surface forms between the model and the field to suggest that processes observed in the model are similar to processes operating in the field. Such a model removes the problems of scaling ratios from consideration. Instead, the assumption is used that the similarity of resulting surface forms between the model and the prototype is sufficient to justify the adequacy of the model, although the procedures and material used in the experiment may be very unlike the field situation. For example, one may use layers of clay and sand to produce "rock" units of different resistance.

These analogies were used extensively in a series of experiments conducted at the beginning of the twentieth century and these experiments were used primarily as hypothesis-generating devices (Hubbard 1907, 1909, 1910), Tarr and von Engeln (1908), Howe (1901), Jagger (1908, Wurm (1935, 1936), Gavrilovic (1972).

Perhaps one of the strongest reasons more small scale studies have not been performed is the unwillingness to accept the assumption that resulting similarity of surface forms between the model and prototype is sufficient justification for the adequacy of the model.

CHAPTER II

EXPERIMENTAL DESIGN

To accomplish the objectives and to eliminate the problems of scaling ratios a large surface was needed over which the application of precipitation could be controlled. Using the knowledge gained during construction of an earlier rainfall-runoff test plot (Dickinson et al, 1967; Holland, 1969), a facility was designed and built by G. L. Smith, Associate Professor of Civil Engineering, Colorado State University. It (Fig. 2.1) was designated the Rainfall-Erosion Facility (REF).

Design of Facility

The REF is a container 30 ft. (9.1 m) wide, 50 ft. (15.2 m) long, and nearly 6 ft. (1.8 m) deep (Fig. 2.). The walls are 0.75 in. (1.9 cm) plywood coated with fiberglass. To reinforce and stabilize the walls, bracings were installed on 2 ft. (0.61 m) centers. Along the outside edge of these supports a 4 in. by 4 in. (10.2 cm by 10.2 cm) wooden beam was laid and pinned to the ground by 0.75 in. (1.9 cm) diameter, 2 ft. (0.61 m) reinforcing rods. A walkway, which extends around the entire facility, was built above the side supports.

To control baselevel and provide an exit for runoff and sediment, a flume was attached to the front of the REF (Fig. 2.1). It was made of 0.75 in. (1.9 cm) plywood supports on 4 ft. (1.2 m) centers. The flume was attached to the REF by a wooden beam which can be raised or lowered by installing or removing similar planks beneath the outlet flume.

The flume is 4 ft. (1.2 m) wide at the outlet but it narrows to 8 in. (20.3 cm) where a sediment splitter was installed . The water and sediment passed through the flume into an 8 ft. (2.4 m) diameter tank where most of the eroded material was deposited. A 4 ft. (2.4 m) segment of flume was attached to the opposite side of the sediment tank and an HS measuring flume (Holton et al, 1962, p. 23) was fixed to this flume sigment for calibration purposes.

Although the surface area of the REF is 1500 ft^2 (139.4 m^2), a border 0.3 m wide was used to prevent water from eroding along the sides of the container. In addition, the two corners near the outlet were not used (Fig. 2.1). Thus, the effective watershed area during the experiment was 1240 ft^2 (115.2 m^2).

Design of Sprinkler System

The sprinkler system utilizes 2 in. (5.1 cm) aluminum irrigation pipes to supply water to lines of sprinklers mounted 10 ft. (3.0 m) apart on both sides of the REF (Fig. 2.1). To obtain the uniformity of rainfall application described by Holland (1969), another supply line down the center of the REF is needed. However, this line of sprinklers would have subjected the surface to disturbance by water drops and leaks from the pipe, and, therefore, it was not installed.

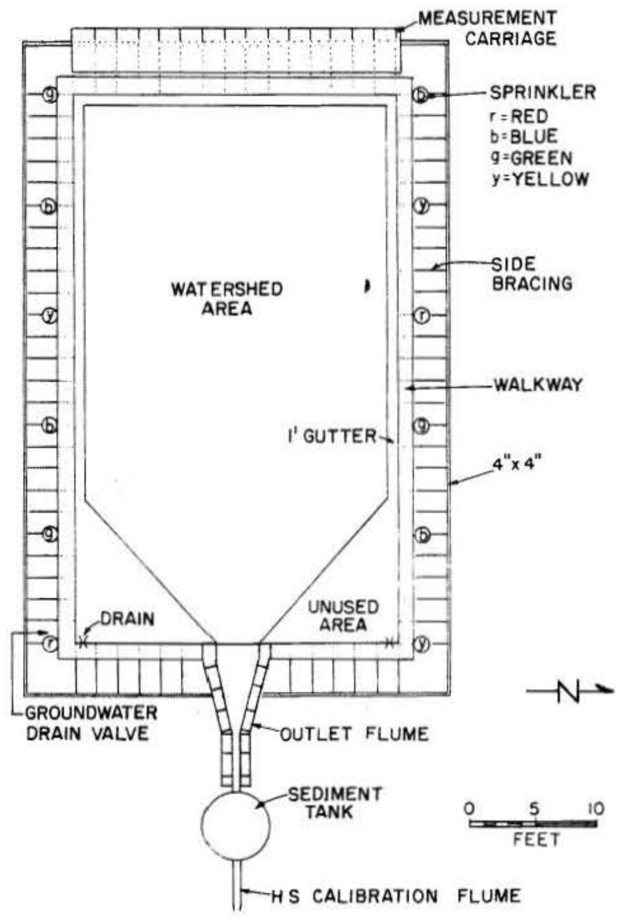

Fig. 2.1. Plan view of the Rainfall-Erosion Facility.

Each sprinkler was attached to the aluminum supply line by a 10 ft. (3.0 m) long galvanized steel pipe. Below the sprinkler head a hydraulic valve activates each sprinkler, and a Watts Low Pressure Regulator controls the water pressure at each sprinkler (Holland, 1969, p. 2-38, Fig. 15). The sprinkler heads are commercial irrigation sprinklers (Rainjet brand with nozzle no. 78).

Sprinklers were grouped into four sets and color coded (Fig. 2.1). Activating different sets of sprinklers yielded different rainfall intensities. With the four sprinkler groups, four rainfall intensities could be obtained. Each of the four sets of sprinklers were controlled by a 24 volt solenoid valve. Thus, the sets of sprinklers could be activated nearly instantaneously.

The pressure regulators controlled both areal distribution and rain drop size. The best areal distribution was achieved with the regulators set at 23 psi. Holland (1969) examined the rain drop size at this pressure and he found that the nozzles produced a higher percentage of drops smaller than 2 mm as compared to natural rainfall. At a rainfall rate of 2 in/hr (0.08 cm/min) the sprinkler produced a drop size distribution with a mode of 1.52 mm and a range from near zero to [illegible] mm. Natural rainfall produces drops with a mode of 2.[illegible] mm and a range between approximately zero and [illegible] mm (Holland, 1969, p. 2-34). Because different intensities are produced by shutting off groups of sprinklers rather than by changing the pressure, the drop size distribution remains constant at the various rainfall intensities. Natural rainfall, on the other hand, shows an increase in drop size with an increase in rainfall intensity.

Calibration of the Sprinkler System

In order to obtain four different intensities of precipitation on the experimental surface, four sets of sprinklers are used in combination. The sprinklers within each set were chosen by trial and error to achieve the best uniformity of precipitation over the REF surface at a particular intensity.

During the first season of data collection there were four extra sprinklers at the end of each of the supply lines. Due to the disturbance of the rainfall pattern by wind, the lowest intensity could not be used during the first season. These four sprinklers were removed when the REF was enclosed in a building prior to the second experimental season, and there was not sufficient space to accommodate them. The building was constructed to eliminate the problems caused by wind, and it also allowed the use of the lowest rainfall rate. The sprinkler configuration for the second season is shown in Figure 2.1.

Calibration of the sprinkler system was accomplished by placing large cans in a grid over the watershed surface after it was covered with a plastic tarp to prevent erosion and infiltration. The placement of these cans and a typical example of the precipitation distribution is shown in Figure 2.2. The highest intensity of precipitation occurred near the center of the REF during all calibration runs. Each calibration run had a duration of 15 minutes and each was repeated. The means and standard deviation of these runs are shown in Table 2.1. The mean rainfall computed for each intensity was compared with the equilibrium discharge at the HS flume, and little difference was noted. The calibration data reflect the change in sprinkler configuration with the three higher intensities yielding higher values during the first experimental season.

Precipitation was not uniform across the watershed, and this is reflected in the standard deviations of Table 2.1. However, the replication of a given areal pattern was excellent. There is an average percentage difference of 2.5 percent between replications for the seven intensities. This experimental error does not appear to be significant. Some random variability in water delivery is inherent in the action of the sprinkler nozzles, which rotate and move up and down in response to the water pressure. Thus, although the rainfall application was not spatially uniform, the repeatability of a particular distribution was consistent through time. Improvement in the uniformity of the rainfall distribution is not possible without the addition of the central supply line and set of sprinklers.

The last column in Table 2.1 is the mean rainfall rate in inches per hour for both replications. These average rates are used as the rainfall rates in the subsequent analysis.

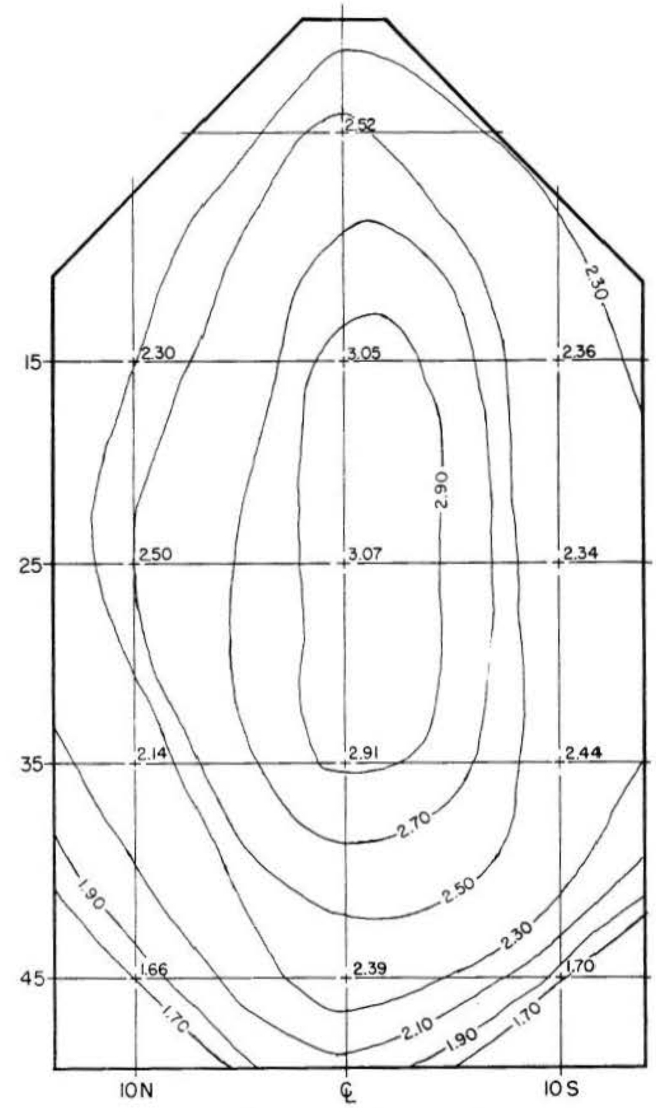

Fig. 2.2. Example of the areal distribution of precipitation showing the changes in intensity over the surface of the REF. Example shown is the maximum intensity for experiment 2 (set 2) with an average rainfall rate of 2.42 in/hr.

Material Used in the Experiment

Suitable material was difficult to find primarily because of the quantity required (9000 cu. ft.; 252 cu. m) to fill the REF. After preliminary tests in a small wooden box, a well sorted sand mixed with approximately one quarter silt and clay was selected to provide both the cohesiveness necessary to establish channels with stable side slopes and to permit rapid erosion.

The material used was over-burden obtained from a local sand and gravel company. It contained the complete range of sand sizes, and approximately 4 percent was larger than 2 mm, which included some clay lumps. About 44 percent of the sediment was in the silt-clay range (less than .062 mm). Mixing this over-burden with an equal amount of commercial grade plaster sand yielded material with approximately 28 percent silt-clay, and a mean grain-size distribution as shown in Table 2.2.

Table 2.1. Summary of precipitation rates available on the REF surface by experimental season

Experiment 1
(Set 1 Data)

No. of Sprinkler Sets Used	Test 1			Test 2			Overall Mean Rate (in/hr)
	No. Obs.	Mean Rate (in/hr)	Stand. Dev. (s)	No. Obs.	Mean Rate (in/hr)	Stand. Dev. (s)	
4	65	2.59	0.25	69	2.64	0.26	2.61
3	65	2.08	0.18	65	2.01	0.20	2.05
2	64	1.24	0.18	64	1.33	0.19	1.29

Experiment 2
(Set 2 Data)

No. of Sprinkler Sets Used	Test 1			Test 2			Overall Mean Rate (in/hr)
	No. Obs.	Mean Rate (in/hr)	Stand. Dev. (s)	No. Obs.	Mean Rate (in/hr)	Stand. Dev. (s)	
4	13	2.41	0.45	13	2.42	0.43	2.42
3	13	1.86	0.30	13	1.81	0.28	1.83
2	13	1.22	0.24	13	1.21	0.27	1.21
1	13	0.84	0.20	13	0.82	0.18	0.83

Table 2.2. Grain size distribution of material used in the experiment. Data given are the mean percent of six samples.

Size	Percent	Cumulative Percent
> 2 mm	1.17	1.17
1 - 2 mm	11.55	12.72
0.5 - 1 mm	15.96	28.68
0.25 - 0.5 mm	17.04	45.72
0.125 - 0.25 mm	15.38	61.10
62μ - 125μ	12.08	73.18
< 62μ	26.82	100.00

Examination of the finer portion of the material (less than .062 mm) by the centrifuge method (Ganow, 1969) revealed that 44.5 percent of the sediment was between the size ranges of 2 and 62 microns. The remaining 55.4 percent was less than 2 microns or in the clay size range. X-ray diffraction of the less than 2 micron material showed quantities of quartz, plagioclase feldspar, and biotite. Approximately half of the clay size material was disordered kaolinite. Thus, after mixing with plaster sand, 12.5 percent of the experimental material was in the size range between 62 and 2 microns and 15.5 percent was less than 2 microns. Approximately 5 percent of the total was clay mineral kaolinite.

Placement of Material

Before construction of the REF, the ground surface was graded to a slope of 1 percent toward what was to be the outlet of the facility. The REF was constructed on the Benton shale, which provided a relatively impermeable layer beneath the container. Above this graded surface, a 6 in. (15.2 cm) layer of 2 in. (5.1 cm) gravel was placed to provide drainage. At the outlet end of the facility, drainage tiles were installed in the gravel with a slope to the southeast corner of the container. A valve was installed on the end of this drainage pipe to control the flow of water out of the ground water system.

Nearly 5 ft. (1.5 m) of the experimental material was placed in 10 in. (25.4 cm) layers above the gravel base. Raking removed larger sized particles, and the layers were compacted by rolling. The final upper surface was graded toward the outlet.

Data Collection

In order to measure distance and elevation within the REF, a carriage was built to span the width of the facility. The carriage rolls on tracts fixed to the walkway. A 4 in. (10.2 cm) I-beam mounted on the carriage supports a point gage set on roller. At any particular location in the facility, the position down the track (the X direction) is recorded by means of a measuring tape fixed along the length of the REF. The Y position is obtained by the position of the point gage with reference to a tape fixed across the carriage. Distance from beam to surface is measured by the point gage. Thus, X, Y, and Z values for any point in the watershed can be obtained, and maps of the drainage system can be prepared.

In order to correct the sag found in the 30 ft. (9.1 m) I-beam a spring system under the beam was incorporated into the design. In addition, the tracks were shimmed to provide a level base for the carriage. Both these techniques did not entirely adjust the measuring carriage to an absolutely horizontal system for any position on the watershed. Therefore, a correction grid for the I-beam was established at 5 ft. (1.5 m) intervals over the watershed surface. These readings of departures of the beam from level were utilized in a computer program to correct the point gage readings (Z values). By taking data on the network in a regular sequence, the computer program could reproduce the stream network and calculate individual stream lengths and gradients.

In addition to mapping from the carriage, a Wild RC-8 aerial camera was used to obtain a record of watershed changes. The camera was bolted to a cage and hoisted 50 ft. (15.2 m) above the facility by a hydrocrane. Two pictures were taken at this height to give stereo coverage of the watershed surface. Targets along the walkway (three on each side) provided the necessary control to permit measurements to be made from the photographs. A Kelsh plotter was used to take X, Y, and Z data at stream junctions and to produce a map of the drainage network, and to calculate stream lengths, gradients, and other geomorphic variables (Barnes and Parker, 1971).

Experimental Procedure

During each of the two experimental seasons, an attempt was made to follow the complete evolution of the drainage pattern. To determine if changes in the initial slope and baselevel changes would affect the resulting pattern, each season was begun with a different set of initial conditions. Data from the first season's network are identified as set 1 and the second season's network is identified as set 2 (See Appendix A for maps of all networks, and Table 2.4 for a summary of the experiments.)

The plan to follow each network through it's evolution was not entirely successful. Dissection of the initial surface was complete during the first experimental season (set 1 data), but documentation of complete erosional reduction of the basin was not possible because the first experiment was terminated due to cold weather. Thus, during the second experimental season (set 2 data) the procedure was modified to insure that the later stages of development would be documented.

The experimental procedure was characterized by caution. The facility and the material to be eroded were essentially untested and no guidelines from previous studies were available. Therefore, instead of lowering baselevel to a depth necessary for complete dissection of the basin at the beginning of the experiment, baselevel was lowered in small increments.

Procedure for Experiment 1 (Set 1 Data)

The basin surface was graded into two intersecting planes (Fig. 2.3) to permit the development of an integrated drainage network at the beginning of experiment 1. The maximum slope of this surface was 0.75 percent toward the outlet. In addition, baselevel was lowered 0.74 ft. (0.22 m) before precipitation was applied.

Initially, precipitation was applied at the highest intensity (2.61 in/hr). At the end of two hours, the drainage network was mapped and the main channel profile was measured from the measurement carriage. This process was repeated five times or until ten hours of high intensity rainfall had been delivered to the surface. Thus, five maps at the same baselevel were made during the initial development of the network. These data represent a data subset which is referred to as set 1, subset 1 (Table 2.3).

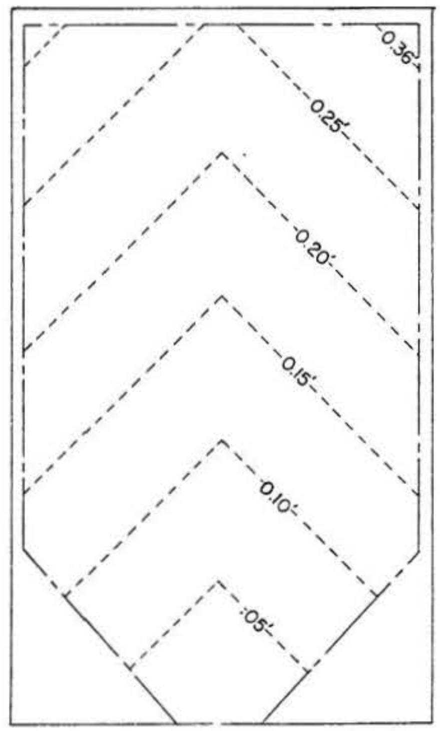

Fig. 2.3 Topographic map of the initial surface for experiment 1 (set 1 data).

Precipitation was applied for four more hours when it was determined that the network had essentially ceased to grow at that baselevel. Aerial photographs were taken before baselevel was lowered another 0.3 ft. (0.1m) to rejuvenate the network and to continue the network growth into the undissected parts of the basin. Water was then applied for 13 hours until network growth had again essentially ceased at that baselevel, when another set of aerial photographs were taken. This sequence of baselevel lowering, rejuvenation of the drainage pattern, and the taking of a pair of stereo photographs at maximum growth was repeated five times. At the end of this sequence of runs the network had reached what appeared to be a maximum development within the watershed. The final photographs were taken after 77.5 hours when 21,798 cu. ft. (610.3 cu.m) of water had been delivered to the surface. This, then, makes up a second subset of experimental data, which is referred to as set 1, subset 2, and contains data for five networks that developed following baselevel lowering. (Table 2.4)

Table 2.3 summarizes data for this first series of experiments. In addition to the network maps a profile of the main channel was taken every two hours and sediment yield from the basin was collected 2 to 3 times each hour.

Table 2.3. Summary of network statistics from experiment 1 (set 1) and experiment 2 (set 2).

Set	Subset	Network	Accum. Amount of Water Over System (ft^3)*	Relief (ft)**	Drainage Density (ft/ft^2)
1	1	1	504	0.985	0.064
		2	1008	0.985	0.098
		3	1512	0.985	0.192
		4	2016	0.985	0.242
		5	2520	0.985	0.281
1	2	1	3528	0.985	0.353
		2	6804	1.280	0.423
		3	12096	1.580	0.542
		4	16380	2.186	0.632
		5	21798	3.069	0.754
2	1	1	504	1.598	0.134
		2	1008	1.578	0.311
		3	2520	1.578	0.406
2	2	1	2520	1.578	0.406
		2	8316	1.744	0.457
		3	26712	2.559	0.496
2	3	1	19152	2.559	0.482
		2	26712	2.559	0.496
		3	37800	2.559	0.460
		4	54432	2.559	0.366

*Used as a measure of time.

**Difference in feet between the highest point in the basin and the lowest point (the outlet).

Procedure for Experiment 2 (Set 2 Data)

For the second experimental season, the surface was again graded to two intersecting planes, but the overall slope was increased to 3.2 percent. In addition, the baselevel was not lowered before precipitation was applied (Table 2.4). With these different initial conditions, data on network growth were taken from the measurement carriage at 2, 6, and 10 hours when maximum growth of the pattern for that initial relief had been attained. This data group contains information on three networks, and it is identified as set 2, subset 1. It is directly comparable to set 1, subset 1 except for the changes noted in the initial conditions.

To rejuvenate the network, baselevel was lowered 0.16 ft. (0.05 m) and precipitation was then applied for 23 hours at which time maximum growth of the network for that baselevel was achieved, and the system was mapped. Baselevel was again lowered another 0.91 ft. (0.28 m), and the network was mapped when maximum growth was attained. Using these two networks and the last network from subset 1 when maximum growth had been achieved, three drainage patterns are available that represent maximum development of the network for individual baselevels. These three networks form set 2, subset 2 (Table 2.4).

On the last baselevel lowering, four networks were actually mapped including the one used in subset 2. These four networks are grouped into one subset (set 2, subset 3).

The two subsets in set 1 and the three subsets in set 2 represent the majority of data used in this report. However, a later study provided data on one network formed at an initial slope of 12.1 percent. The initial surface was graded to two intersecting planes, as before, so that an integrated drainage pattern was produced. Baselevel was lowered 0.33 ft. (0.10 m) before precipitation was applied. Due to the experimental design, the watershed area was reduced to 581.27 ft^2 (177.2 m^2) or approximately half of the area used previously. After two hours of running, the network was compared with the first network in set 1, subset 1 and the first network in set 2, subset 1. Because there is only one network, it will not be given a separate set number, but during discussion of the data it will be described as being derived from this separate experiment.

Hydrologic Data

In order to examine changes, if any, in the hydrologic response of the basin to changes in its geomorphic configuration, a series of hydrographs were generated at the available intensities. A 60 degree V-notched weir was used to measure these hydrographs. This weir was used rather than the HS flume to avoid excessive storage and translation difficulties. The weir box, attached directly to the baselevel contained a storage area below the V-notch of the weir blade to collect the sediment produced during hydrograph runs.

The procedure was to generate an equilibrium hydrograph by applying 10 to 15 minutes of precipitation. This was followed by a series of one minute precipitation events (Fig. 2.4). The equilibrium runs helped to negate the influence of infiltration, and the series of one minute hydrographs were replicated to insure an accurate representation of the hydrograph shape.

The series of hydrographs were produced after all but one aerial photograph was taken. That is, there is a set of hydrographs for networks 1, 3, 4 and 5 in set 1, subset 2. The hydrographs, therefore, were generated on basins that showed an increase in total channel length and in overall relief. These differences would, it was felt, produce the greatest differences in the hydrographs. Although these hydrographs show variability caused by problems with wind, the sensitivity of the hydrograph recordings suggests that even more subtle variations in runoff could be detected.

During the second experimental season, hydrographs were only generated after baselevel was lowered the final time. That is, there are four sets of hydrographs from the four networks of set 2, subset 3. Thus, all four sets of hydrographs are on one baselevel but have different values for total length of channel.

No hydrograph information was obtained for the networks as they initially developed (i.e., subset 1 of both data sets). This is indeed unfortunate because there were dramatic changes in the geomorphology of the basin during this portion of the evolution. However, sediment yields were so high at this time that they interferred with the hydrologic record, and attempts to obtain hydrographs were discontinued.

Besides hydrograph data, sediment yields produced by a one-minute-duration rainfall event were obtained by collecting 3 or 4 samples at the outlet for each hydrograph. This was done for networks 1, 3, 4 and 5 of set 1, subset 2.

In summary (Table 2.4), two experiments were performed. The first experiment, data set 1, had a 0.75 percent initial slope toward the outlet and baselevel was lowered before precipitation was applied.

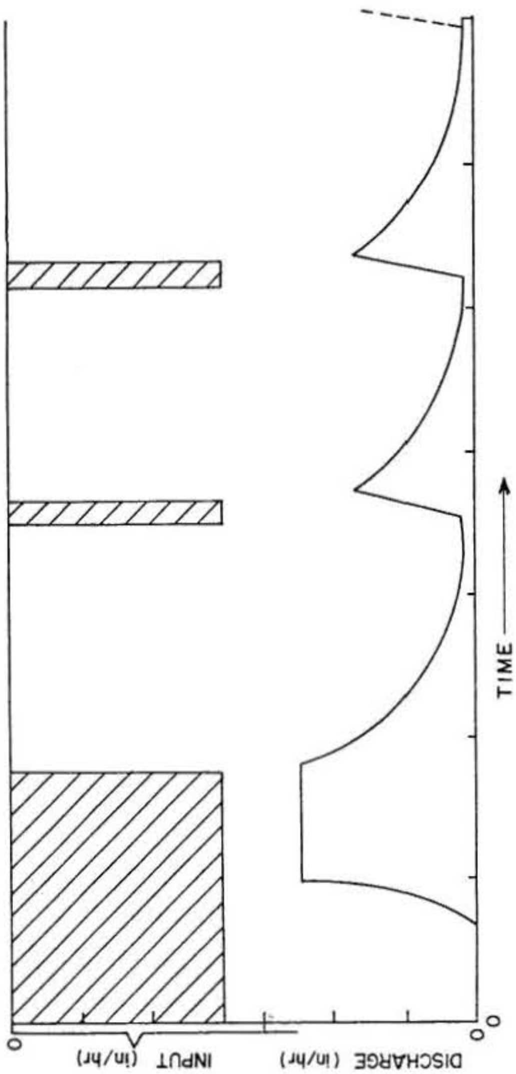

Fig. 2.4. Diagram of the sequence of hydrograph generation at each rainfall intensity on a particular stream network. Equilibrium hydrograph is first run followed by a series of partial equilibrium hydrographs produced by one minute duration precipitation.

This experiment produced the data of set 1, subsets 1 and 2. Subset 1 contains data for five networks. Measurements were taken 2 hours apart starting from initiation of the pattern to near maximum development of the patterns of that particular baselevel. Subset 2 consists of data for five networks, which represent maximum development of the network at each of five different baselevels. Each network was photographed and mapped, and hydrologic data were collected for four of these networks (networks 1, 2, 3 and 5).

Experiment 2 involves networks generated on an initial slope of 3.2 percent with no lowering of baselevel before the experiment commenced. This experiment produced the data of set 2 which contains three subsets. Subset 1 contains three networks which were mapped as erosion progressed with no change in baselevel. Subset 2 contains three networks mapped at maximum extension for a particular baselevel. It is comparable to set 1, subset 2. Subset 3 contains data on four networks developed at a constant baselevel near the end of the second experiment. Hydrologic data were collected for these four networks.

Special Considerations

Several special problems exist with respect to the data collection in the REF. For example, although the rigid boundaries of the REF allow comparison of basin evolution for constant areas, these boundaries also create some unique problems. In nature a watershed competes with neighboring basins, and drainage divides shift and lower with time. However, competition is lacking along the rigid boundary, and the wearing down of divides is very slow at the boundary. Therefore, if baselevel remains constant, relief differences between the highest point in the REF near the back boundary of the facility and the lowest point at the outlet remains essentially constant no matter how much water is applied to the surface. Internally the basin may continue to lose material, internal divides wear down, and overland slopes decrease their gradients, but overall the relief difference between the highest and lowest points remain essentially constant. Nevertheless, the advantages of investigating a basin with constant area outweighs this disadvantage.

Because the length of the watershed remains constant throughout the experiment, a basin relief value, taken as the difference between the highest and lowest points, can be directly compared with another basin relief value and no correction for basin length need be applied. In comparing natural basins it is common to use the relief ratio (Schumm, 1956), which is the difference between the highest and lowest point in the basin divided by the basin length. As the length of the experimental basin remains constant, there is no need to resort to the relief ratio. Therefore, reference is made in the subsequent analysis to "relief from the horizontal." This value is the height difference between two parallel planes one of which passes through the baselevel and the other which passes through the highest point in the basin.

In deriving drainage density for a particular network, the area of the basin is taken as the total watershed area delivering water to the outlet. In this experiment this means that the watershed area is always a constant (115.2 m^2). Because the area of the drainage basin is constant, the total length of channel and drainage density are directly related.

The highest intensity was used to erode the basin from one configuration to another. During experiment 1 this intensity was 2.61 in/hr (0.11 cm/min), and during experiment 2 it was 2.42 in/hr (0.10 cm/min). The percentage difference between these two intensities is 7.5 percent and this is not considered significant. It is unknown whether the use of this one intensity rather than a frequency distribution of all intensities would have resulted in a significantly different drainage pattern. Such a comparison could be the objective of a future study in REF.

Table 2.4. Summary of data sets used in the analysis showing major characteristics of each set.

Set No.	Subset No.	Network Description	General Characteristics
1	1	1 2 3 4 5	Initial conditions -- initial surface slope 0.75 percent, baselevel lowered 0.735 ft. before run 1. All networks on same baselevel as system begins growth on undissected surface.
1	2	1* 2* 3* 4 5*	Initial conditions -- initial surface slope 0.75 percent, baselevel lowered 0.735 ft. before each run. Networks represent maximum extension of growth for a particular baselevel. Relief increases with network number to allow extension of network into the total basin. The first network follows the last network in set 1, subset 1-5 in time.
2	1	1 2 3	Initial conditions -- initial surface slope 3.2 percent, no baselevel lowering before run. All networks on same baselevel as system begins growth on undissected surface.

Table 2.4, Cont'd.

Set No.	Subset No.	Network Description	General Characteristics
2	2	1 2 3	Initial conditions -- initial surface slope 3.2 percent, no baselevel lowering before run. Networks represent maximum extension of growth for a particular baselevel. Relief increases with network number to extend network into total basin. First network is last network in set 2, subset 1.
2	3	1* 2* 3* 4*	Initial conditions -- initial surface slope 3.2 percent, no baselevel lowering before run. All four networks are on same baselevel which is lowest level used in this set. First network is near maximum extension of network into the basin. Network 2 represents maximum extension on baselevel and is also network 3 in set 2, subset 2.

*Hydrograph set generated for this network.

CHAPTER III

GEOMORPHIC EVOLUTION OF DRAINAGE BASIN

W. M. Davis (1909) developed a geographical cycle in which a block of uplifted land proceeded through a cycle of erosional evolution. This was a highly simplified model of landform change through time and it has fallen somewhat into disfavor primarily because of its simplified nature. The importance of this cycle, however, is that it forces the geomorphologist to consider the temporal change of variables and their interaction.

To accomplish the objectives of this study the experimental design is based on Davis' model of an uplifted block of material that is subjected to erosion.

Stages of Basin Evolution

An early but interesting discussion of the evolution of stream networks was provided by W. S. Glock (1931) in which he classed the development of a drainage system into growth stages. This classification is summarized as follows:

1. Initiation
2. Extension (Growth of network)
   a. Elongation (headward growth)
   b. Elaboration (addition of tributaries)
3. Maximum Extension (attainment of complete elaboration of maximum growth of the network)
4. Integration (Reduction of the network)
   a. Abstraction (loss of identity suffered by a secondary stream by encroachment of a primary stream)
   b. Absorption (disappearance of a stream save immediately after rainfall)
   c. Adjustment or aggression (attempt made by main stream to reach the sea by the shortest route consistent with regional slope).

Notice that the numbered categories in the outline above are stages of network evolution and the lettered categories are the major processes and modes of change identified in each stage.

Glock (1931, p. 479) characterized initiation by: (1) a lack of streams over a large percentage of the surface, (2) indefinite termination of many streams without junction with a main stream, (3) the failure of many streams to have started that active conquest of territory so typical of their future histories.

Glock (1931, p. 479) characterized the stage of extension as a period of growth for the initially abbreviated drainage system. Glock envisioned elongation as the active process in this stage by which major streams blocked out the undissected drainage area. This is followed by elaboration, which gradually changes the skeletal form of the initial stream system by means of the addition and growth of minor streams. Glock further stated that the end of extension, which he called maximum extension, the stage of development when the network had grown into all the available drainage area.

The stage of integration is marked by the reappearance of the skeletonized form of the network (Glock, 1931, p. 481). The processes responsible for the loss of channels are abstraction and aggression. The continued lowering of divides does not provide sufficient internal relief to maintain all channels, and some are lost. In addition, continued lateral migration of major streams eliminates small tributaries. This period is marked by piracy and general shifting of individual channels. The net result is a loss of streams and, therefore, in a reduction of the total channel length, which reduces drainage density.

These growth stages are analogous to those observed during the evolution of the experimental network in the REF and, therefore, they provide a framework for the discussion of the experimental results. That is, on the initial surface the netowrk extended to a maximum limit and then began a process of integration during which channels were lost.

Some problems exist with Glock's classification when an attempt was made to apply it to the experimental results. The period classed as initiation could not quantitatively be separated from any other part of extension and was dropped from any separate discussion. Although elongation and elaboration were recognized, a quantitative distinction between them was difficult to obtain. Also, it appears that Glock felt that the process of elaboration followed in time the period of elongation. This sequence was not observed in the experimental data. Rather, the dominance of one of these processes at a particular time in the evolution of the basin appears to result from different initial conditions as will be shown.

Maximum extension was evident by observation, and it can also be identified by plotting a variable such as drainage density through time.

Integration in the experimental facility results primarily from abstraction and adjustment by aggression. Absorption, a process of integration identified by Glock, was not obvious. This is not to say that such a process is not important in the field, rather, the experimental design did not permit such a process. High intensity precipitation was applied for long periods of time. In the field long periods of no rainfall and short periods of high intensity rainfall combine to make absorption more important. Hence, integration is described under the heading, "Abstraction," as it was the dominant process observed.

With these exceptions, the outline of evolution as proposed by Glock serves as an outline of the dominant events observed in the evolution of the watershed of the REF.

Models of Growth

Glock's outline follows a temporal sequence but it is different from Davis' model of landscape evolution in that it focuses on the processes of network evolution. Davis' model is oriented toward the description of the surface forms and does not attempt a description of processes.

There has been little discussion in the literature of the different types of network growth. However, there have been numerous computer models developed which simulate natural stream networks. These simulations have taken one of two directions. One, the model first proposed by Leopold and Langbein (1962) generates a stream network by growth of streams from divide to mouth. Growth begins at the sources located on the basin divide and it continues downstream to establish the master stream at the outlet. Because of this mode of growth, there is, in fact, no correspondence with a natural drainage basin in the manner in which the model network grows. The only correspondence with a natural system is obtained when the total drainage system has developed.

Contrary to the assertion by Leopold and Langbein (1962), p.A14), this model is not analogous to the one proposed by Horton (1945, p. 335). Horton suggested that on a steep, newly exposed surface a series of parallel rills would develop and that, with time, crossgrading and micropiracy among these rills would produce an integrated network. For the Leopold-Langbein model to be an effective model of this process, the initial rills would have to develop over the length of the available area and the integrated network could then be produced by piracy and crossgrading.

The second type model reflects headward growth (Smart and Moruzzi, 1971; Howard, 1971). In this model networks develop fully at the edge of the as yet undissected area. That is, the channels grow headward and bifurcate.

The two models (Horton and headward growth) that have been identified represent two different forms of network growth. Whether there are other growth models is unknown, but these two are so different that they may represent two end members of a continuum of different growth types. On one extreme is the Horton model in which parallel rills develop almost instantly over the surface, and with time the pattern of the network is formed by crossgrading and micropiracy. That is, internal changes occur in the network through time.

At the other extreme is the headward growth model in which a "wave of dissection" can be envisioned at the sources of the first order channels. As this wave progresses into the undissected basin, the finger tip channels lengthen and bifurcate leaving behind a channel system that is fully developed. In this developed portion of the network few additions or abstractions of channels are made during the continued extension of the network. That is, the significant feature of this model is that the network is fully developed as the wave of dissection passes a particular point.

Evolution of Drainage Networks

The evolution of the experimental drainage patterns during the experiments with different initial conditions (Set 1, Set 2) is described in this section. Drainage density change is used to document network changes.

Stages of Network Evolution

Drainage density for both networks is plotted through time by using the amount of water that passed across the baselevel of the basin as a time function (Fig. 3.1). A logarithmic plot is used primarily to accommodate the large range in time values. Initial conditions considerable alter the drainage density values through time, but both sets of data follow the same overall trend with drainage density increasing to a maximum value. In the second data set this maximum is followed by a decrease of drainage density. The decrease is inferred for set 1 data, because the experiment was concluded before additional data were obtained.

The categories of growth described by Glock (1931) can be identified on these curves. There is no clear division between initiation and extension (Fig. 3.1). At maximum extension, drainage density reaches a maximum. After maximum extension, abstraction begins, as is indicated by decreasing values of the drainage density. Given an undissected surface and sufficient time, the general relation of drainage density with time will show this curvilinear form.

Initial Differences in Networks

The initial conditions alter the form of the drainage density curve with time (Fig. 3.1). After two hours of run on each experimental surface (first data point in each curve), the basin on the steeper initial slope and with no baselevel change (set 2) yields a higher drainage density value (Curve A). However, this network has a lower drainage density value at maximum extension. These two major differences result from different modes of growth.

After the first two hours of run (Appendix A, set 1, subset 1, network 1, and set 2, subset 1, network 1) several differences are noted between the drainage patterns. The drainage system occupies more of the available area after two hours of run, when the network is formed on a steeper initial surface slope (set 2) with no change in baselevel. Also, the low-order tributaries are longer, which results in a higher drainage density. The difference in lengths of first order channels is apparent from the relative frequency histograms of first-order Strahler stream lengths. The histogram for the network on the lower initial slope with a baselevel change (set 1) is right skewed with a geometric mean length of 1.12 ft (Fig. 3.2) whereas, the histogram for the initial network on the steeper initial slope with no baselevel change shows a very different rectangular shaped distribution (Fig. 3.3) with a poorly defined mode. Lengths range from 0.4 ft. to 10 ft. in an almost uniform fashion, and the geometric mean length is 3.05 ft. (Table 3.1).

Using a t-test at the one percent level of significance, a value of 3.56 for the t statistic shows that the difference between these two geometric means is statistically significant. Thus, with changes in the initial conditions, the initial networks are different.

Unfortunately, the differences observed were the result of varying two components in the initial conditions--the initial slope and baselevel changes. As stated previously, however, there is an additional network available from another experiment run in the REF (Fig. 3.4). The total relief of this third network was 2.894 ft. and baselevel was lowered 0.33 ft. before the experiment commenced. This gave an initial slope of 12.1 percent. Due to the design of this experiment, the watershed area was reduced to 581.27 ft^2 or to approximately half the area of the basins that produced data sets 1 and 2. This network, had a steeper initial slope than either of the other two networks, but because baselevel was lowered before the experiment began, it is comparable with the network on the lower initial slope of 0.75 percent (set 1). The

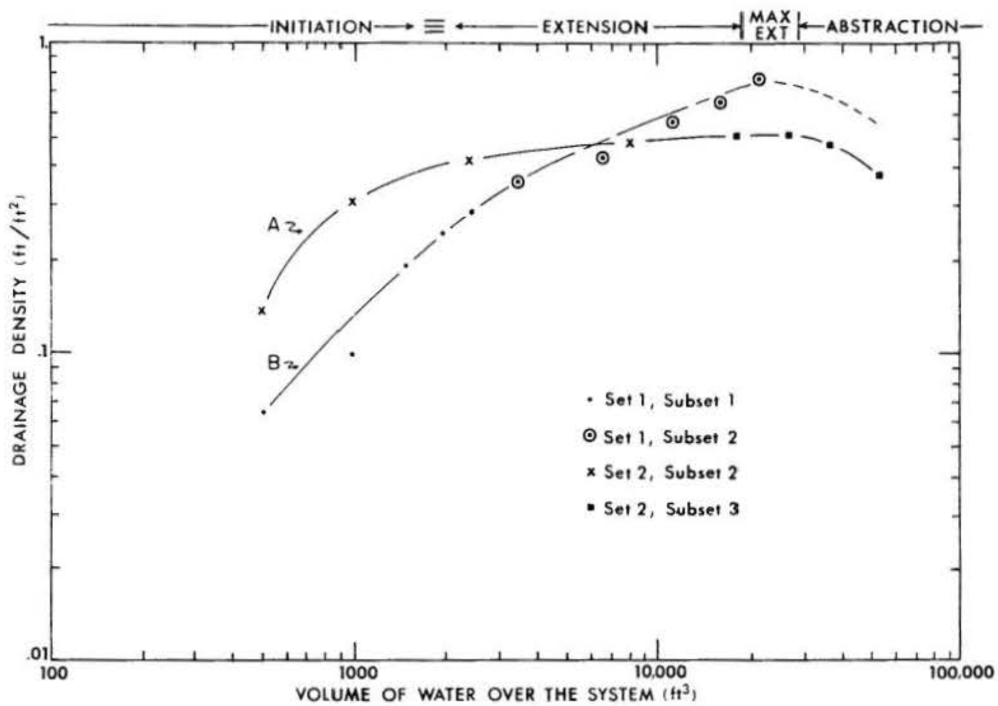

Fig. 3.1 Changes in drainage density during basin evolution for experiment 1 and 2.

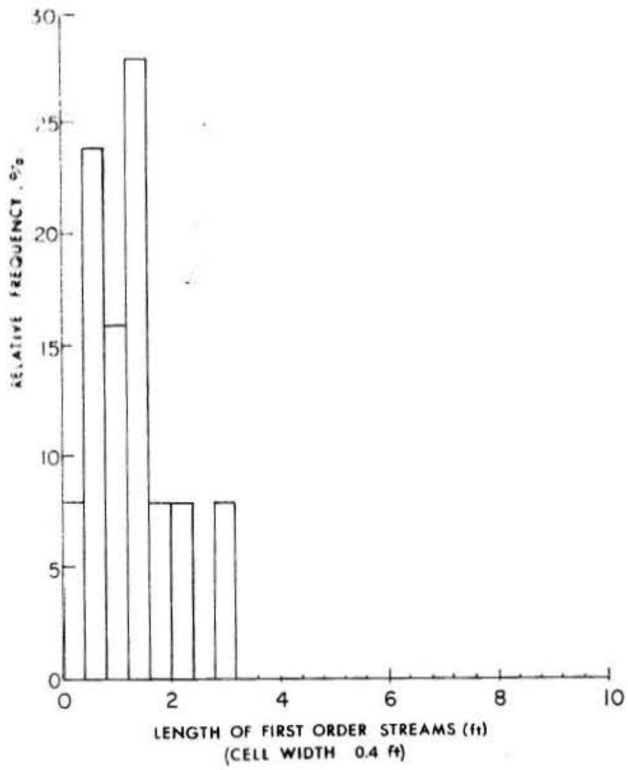

Fig. 3.2. Relative frequency histogram of Strahler first-order stream lengths for first network on initial slope of 0.75 percent with a lowering of baselevel (network 1, set 1, subset 1).

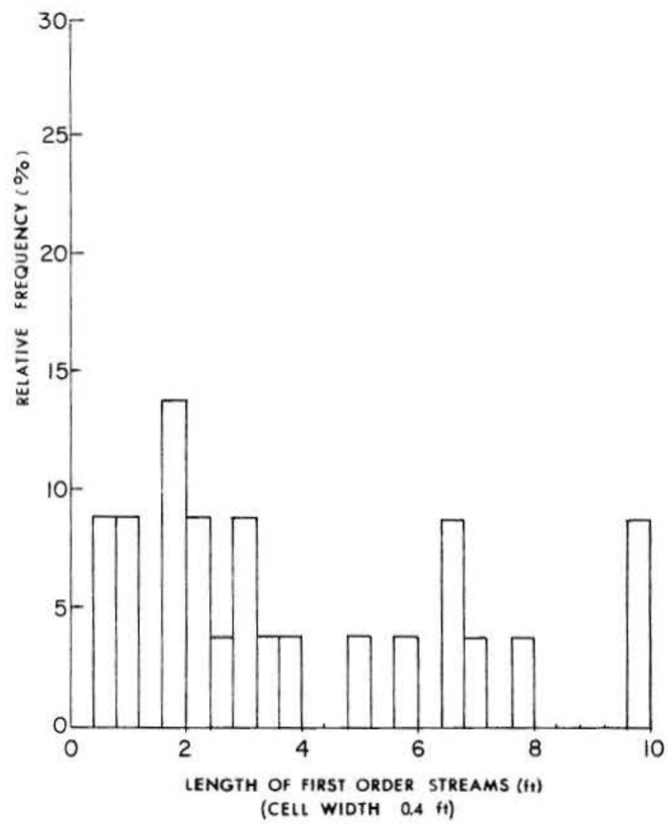

Fig. 3.3. Relative frequency histogram of Strahler first-order stream lengths for first network on initial slope of 3.2 percent with no lowering of baselevel (network 1, set 2, subset 1).

relative frequency histogram of Strahler first-order channels for this network (Fig. 3.5) shows again the right skewed distribution similar to that for the network on the initial slope of 0.75 percent (Fig. 3.2). This distribution of stream lengths has a geometric mean length of 1.33 ft (Table 3.1). A t-test was again employed, and a t statistic of 0.437 was obtained, which at the one percent level of significance, allows the acceptance of the hypothesis that the geometric means are equal between the initial network in set 1 (Fig. 3.2) and this network (Fig. 3.5).

Table 3.1. Summary of statistics of first-order streams from initiation to maximum extension.

Network	Number of Streams	Geometric Mean (ft)	Standard Deviation
Set 1, subset 1			
1	25	1.12	1.95
2	38	1.06	2.27
3	74	1.54	1.84
4	104	1.43	1.92
5	114	1.49	1.86
Set 1, subset 2			
1	163	1.13	1.88
2	220	1.01	1.90
3	277	0.95	2.03
4	353	0.83	1.81
5	485	0.79	1.84
Set 2, subset 1			
1	24	3.35	2.40
2	64	3.17	1.98
3	81	3.05	1.82
Set 2, subset 2			
1	*	*	*
2	103	2.60	1.64
3	152	1.52	2.02
Extra network on 12.2% slope**			
1	59	1.33	2.07

*Network the same as network 3, set 2, subset 1.

**This is the initial network from separate experiment on 12.2% initial slope with a baselevel change before the initiation of the run.

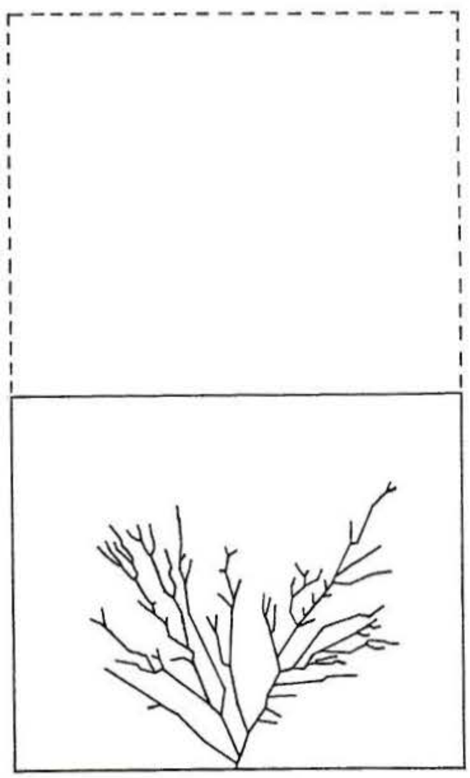

Fig. 3.4. Network from additional experiment on initial slope of 12.2 percent with a lowering of baselevel.

It appears that a steepening of the initial slope produces the network more quickly in response to the added relief in the basin. Lowering the baselevel before running, however, changes the mode of growth. A lowering of the baselevel produces a network that develops fully as it grows headward. This is headward growth, as discussed earlier. A knickpoint develops at the outlet, where the baselevel has been lowered, and as this knickpoint migrates upstream, the channels grow and bifurcate to produce a fully developed network in which little internal growth occurs. In Glock's terminology both elaboration and elongation progress simultaneously.

In a situation where the baselevel is not lowered before network development, long tributary channels develop. Later the area between these tributaries is filled by additional tributary growth. This latter process was identified by Glock as elaboration.

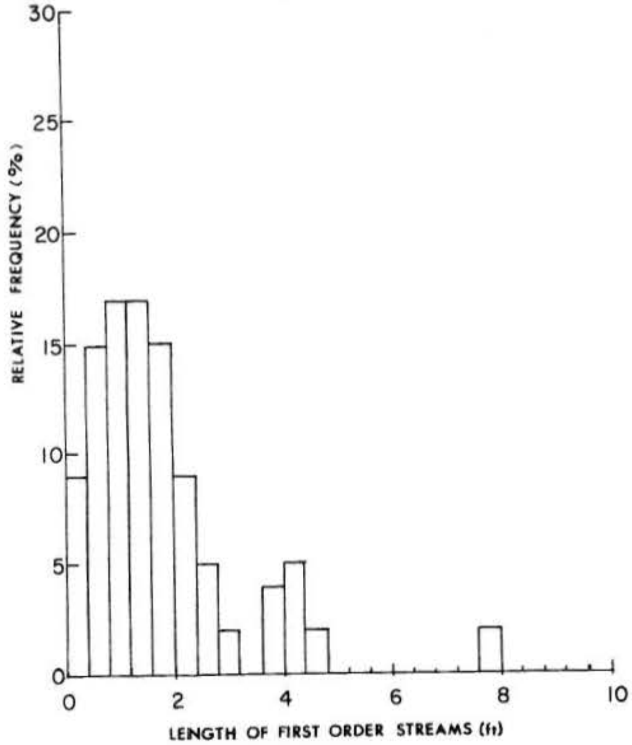

Fig. 3.5. Relative frequency histogram of Strahler first-order stream lengths for network from additional experiment on 12.2 percent initial slope with a lowering of baselevel.

Differences in Networks at Maximum Extension.--The network formed on the steeper initial surface (set 2) does not have as high a drainage density value at maximum extension. At maximum extension there is a 33 percent difference between the drainage densities of the two patterns. Although the differences between the two drainage density values does not appear greatly different when calculated in feet, the difference is 1361 mi/mi^2 when calculated in the conventional units.

Values of drainage density reported in this research are extremely high in comparison with natural systems. The closest values are those reported by Smith (1958, p. 999) who measured values of 200 to 400 mi/mi^2 in Badlands National Monument, South Dakota, and by Schumm (1956, p. 616) who measured values as high as 1,100 to 1,300 mi/mi^2 in badlands at Perth Amboy, New Jersey. This results from the easily eroded material used, the lack of impedance to erosion (e.g., no vegetation), and the careful mapping of the drainage system. Such high values are inherent in experimental studies.

The relative frequency histograms of Strahler first-order stream lengths for the two experiments at maximum extension show a right skewed distribution (Fig. 3.6 and 3.7). From initiation to maximum extension the histograms of set 1 data show little change. On the other hand, the changes in the appearance of the histogram on the steeper initial slope (set 2 data) are dramatic (Fig. 3.7). Initially the histogram was rectangular, but at maximum extension the histogram of first-order stream length is right skewed, and it is similar to the set 1 distribution. At maximum extension, the range of lengths is greater, and the geometric mean length is larger for the set 2 data. The geometric mean length of first-order channels at maximum extension for the first data set is 0.79 ft. whereas the geometric mean length of these channels at maximum extension on the steeper surface is 1.52 ft. (Table 3.1). A t-test yields a t statistic of 3.97 which is significant at the one percent level; thus,

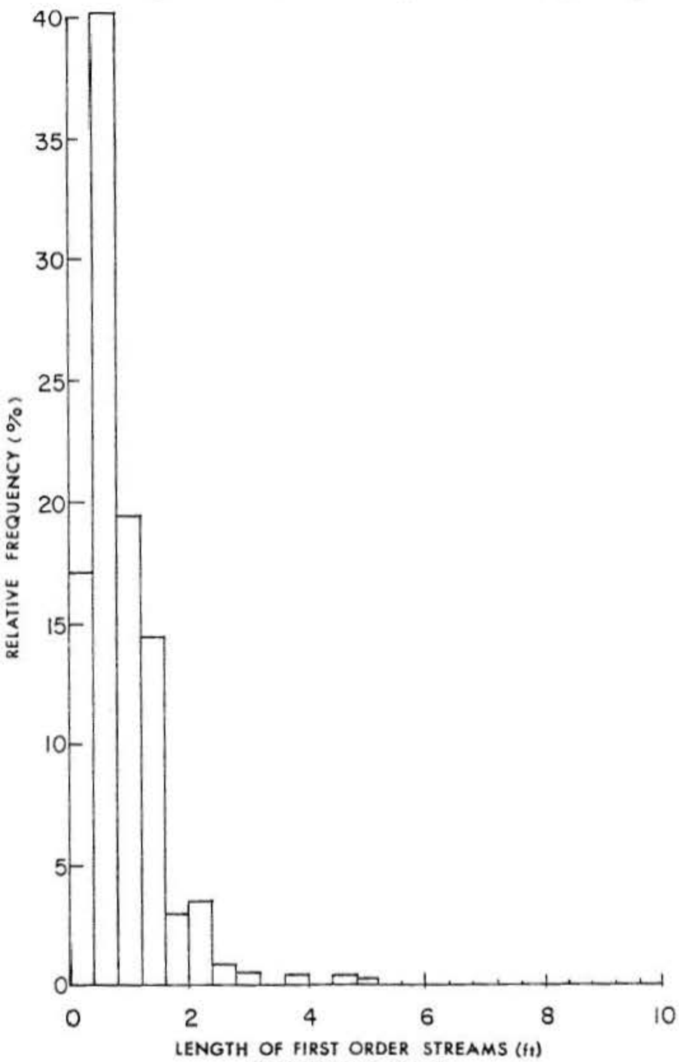

Fig. 3.6. Relative frequency histogram of Strahler first-order stream lengths for network at maximum extension on initial slope of 0.75 percent with a lowering of baselevel (network 5, set 1, subset 2).

the two means are statistically different at maximum extension.

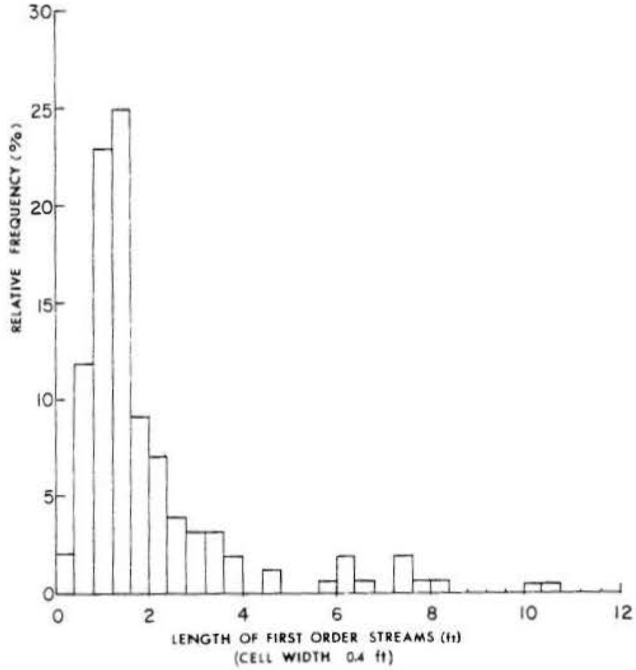

Fig. 3.7. Relative frequency histogram of Strahler first-order stream lengths for network at maximum extension on initial slope of 3.2 percent with no lowering of baselevel (network 3, set 2, subset 2).

In summary, the different initial conditions significantly influence network development. This influence is observed even at maximum extension. With baselevel lowering, first-order streams maintain a consistency in length during growth as shown in the histograms of length. Thus, first-order streams exhibit a regularity in the length they attain before bifurcation.

With no baselevel change, initial channels are long and develop over large portions of the watershed. Further network growth produces a number of first-order streams branching from these initial channels. Histograms of first-order stream lengths show a decrease in the mode and mean lengths through time. Also, drainage density values at maximum extension show that total channel length is less than during the first experiment.

<u>Changes in lengths of first order stream lengths.</u> Changes in first-order stream length have been noted between initiation and maximum extension. The focus on the first-order channels is important because these channels reflect the growth of the network. For the networks already examined, the first-order stream distribution is markedly right skewed. All of the histograms except that of Fig. 3.3 show this form of distribution and, therefore the geometric mean is used to characterize central tendency in these distributions.

To examine changes in the geometric mean length of first-order channels through extension to maximum extension, the mean lengths are plotted against a percent time to maximum extension (Fig. 3.8). This time ratio is obtained by dividing the cubic feet of water applied to the system for a particular network by the amount of water applied at maximum extension. Thus, 100 percent represents the time at maximum extension.

Figure 3.8 shows a least squares fit of a line through both sets of experimental data. The equation of the line through the first set of data on the 0.75 percent initial slope with a baselevel change is:

$$\overline{L}_1 = 1.32 - .006\ T_e \qquad (3.1)$$

where $\overline{L}_1$ = geometric mean length (ft) of Strahler first order streams

T_e = ratio of time of network I to time at maximum extension times 100.

The equation for the line through the second set of data is:

$$\overline{L}_1 = 3.26 - .018\ T_e$$

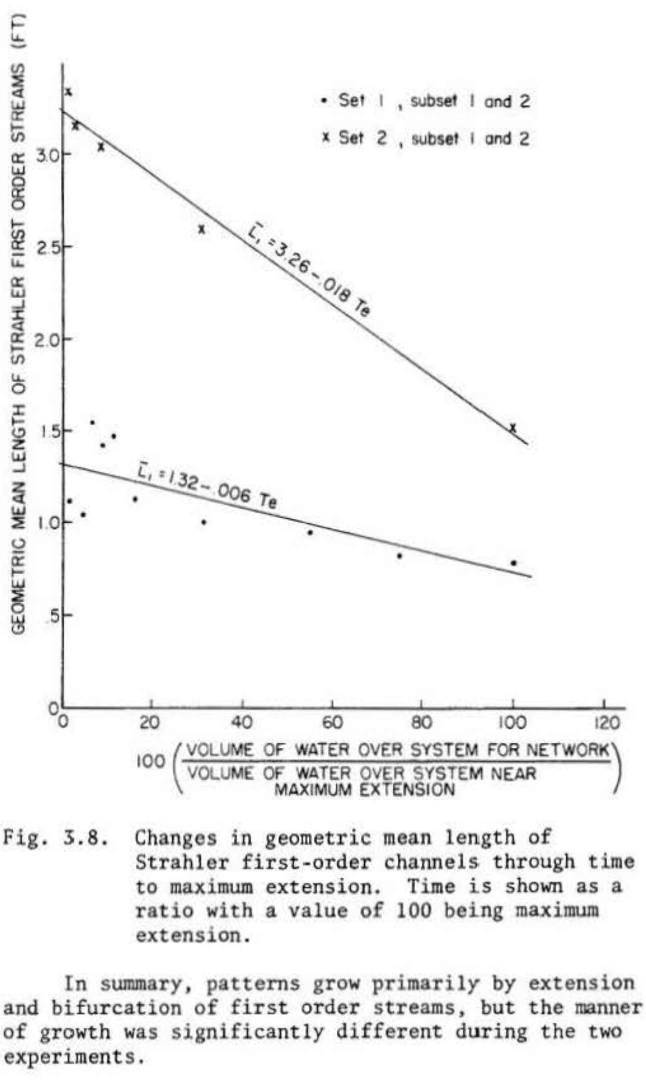

Fig. 3.8. Changes in geometric mean length of Strahler first-order channels through time to maximum extension. Time is shown as a ratio with a value of 100 being maximum extension.

In summary, patterns grow primarily by extension and bifurcation of first order streams, but the manner of growth was significantly different during the two experiments.

Growth Models

The differences in the drainage networks can be related to differences in the growth of the two networks which in turn reflect different initial conditions.

On the lower initial slope of 0.75 percent with a baselevel change before the initiation of the experiment, the relative frequency histograms of Strahler first-order stream lengths are nearly equivalent at the beginning of extension and at maximum extension, and the geometric mean length of first-order streams is stable through time. Also the drainage density and, therefore, the total channel length increase in a regular fashion (Appendix A). These observations suggest that this network is growing headward in a regular fashion as a wave of dissection progresses into the undissected area. This mode of growth is characteristic of the headward growth model.

The network on the steeper initial slope with no baselevel change produces a relative frequency histogram of Strahler first-order stream lengths that is almost rectangular for the first network. This distribution reflects the long first-order channels that develop rapidly into the undissected area and "block out" a large portion of the watershed. Later development includes the growth of tributaries from these long first-order channels. Again, the drainage density increases with time, but the rate of increase is slow, and the value at maximum extension is not as high as for the other network.

The initial histogram and the one at maximum extension for the steeper initial surface are very different. Starting with a nearly rectangular distribution, the distribution becomes right skewed. This change in the histograms reflects subsequent development of smaller first-order channels in the undissected area between the initially long first-order streams. Although not exactly equivalent this mode of growth suggests the Horton model of network development. Long tributaries initially develop very rapidly to produce a high value of drainage density (Fig. 3.1), but then the increase of drainage density slows after much of the area has been dissected. Changes in channel length occur by internal elaboration of the network, and abstraction and piracy change the network configuration. Thus, the growth is nearly like the Horton model, but it does maintain some of the attributes of the headward growth model.

These changes in initial conditions and the resultant changes in the mode of growth indicate two types of network growth--headward growth and Hortonian growth. Differences in the type of growth are directly related to the initial conditions.

Internal Variations in Drainage Density

Although drainage density for both networks changes in a regular fashion as seen in Figure 3.1, an examination of individual networks suggests that a mean drainage density value does not adequately represent a network at a point in time. The problem is to identify the differences in drainage density in different parts of a basin. For example, the area near the outlet has a lower drainage density than an area near the watershed border, as maximum extension is approached (e.g., Appendix A, set 2, subset 2, network 3).

To examine these internal drainage density changes, one subset of data will be used (set 2, subset 3). The differences, observed in this subset (Table 2.4), are similar to differences observed throughout the experiment. Additional evidence of such changes will be given in the next chapter.

In order to compare drainage density within a network two equal areas were delineated. Each area is 620 ft^2 or half the total watershed area. The first area was defined around the outlet and the other around the border. These artificial divisions are shown schematically in Figure 3.9. Table 3.2 gives the total channel length and drainage densities for the four networks in the data set.

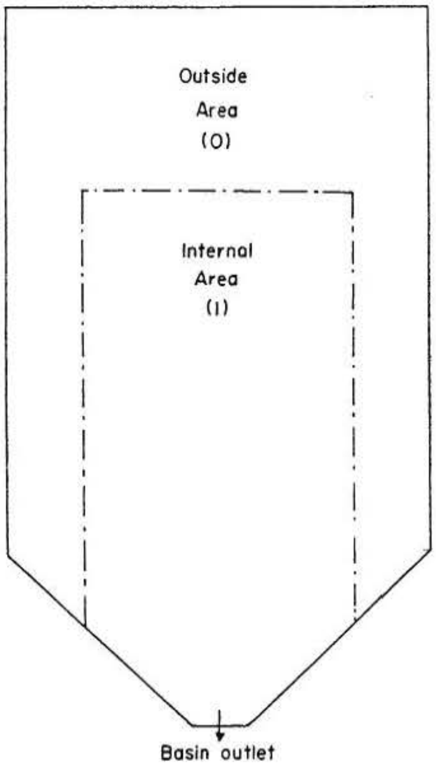

Fig. 3.9. Definitional sketch of manner in which drainage area was divided into equal areas in order to compute drainage density.

The differences between the sub-areas can be shown by the ratio of drainage density for the two parts of the basin (Table 3.2). These differences in drainage density indicate that even before maximum extension the abstraction process is at work near the outlet or "older" part of the basin.

Summary. By Plotting drainage density through time, a curvilinear relation is obtained which can be subdivided into periods of extension, maximum extension, and abstraction (Fig. 3.1). Although this general relation appears definitive with little scatter to the data points, there is a confounding of the relation due to changes in baselevel during the experiment. These changes in baselevel were the driving force in the experiment which allowed drainage density to increase.

If during the additional experiment initial conditions were held constant but a change in either the geology (amount of clay in the material) or the climate (the intensity of the rainfall) was simulated, the result would probably be a family of curves. Such a series of curves would not overlap but would be stacked one on top of the other.

Changes in drainage density with time were noted by examining the differences at initiation and at maximum in the appearance of the network, the value of drainage density, and in the relative frequency histograms of Strahler first-order stream lengths and the geometric mean extension. These differences were attributed to differences in the mode of network growth, headward growth and Hortonian growth. The first experiment produced little difference in the histograms of the first-order stream lengths between initiation and maximum extension. This was taken as an indicator of regularity of growth in this experiment, and it showed the tendency for the network to develop fully as it grew.

The second experiment, with different initial conditions, produced a channel system which "blocked out" a large portion of the area during an initial period of elongation with tributaries filling in the undissected portion of the basin later during elaboration. This difference in growth was reflected in the shape of the first-order stream length histogram and its changes through time. Also, drainage density was significantly less following Hortonian growth.

Table 3.2. Separation of drainage network into two equal area sub-basins to compute drainage density (Dd) in set 2, subset 3

Network	Total Channel Length (ft)		Dd (ft/ft^2)		Ratio of
	Internal (I)	Outer (O)	Internal (I)	Outer (O)	Dd_I to Dd_O
1	288.68	309.15	0.463	0.496	0.933
2	262.64	352.62	0.422	0.566	0.746
3	230.93	339.65	0.371	0.545	0.681
4	212.43	241.25	0.341	0.387	0.881

The drainage density values for the internal sub-area continually decrease with time (Table 3.2). Drainage density increases in the outer sub-area to maximum extension (network 2), and thereafter a decrease in the drainage density is noted. In summary, these observations show a decrease in the drainage density near the outlet and main channel before maximum extension is reached. The area nearer the watershed border shows a continued increase in drainage density to maximum extension and a lessening of these values only after maximum extension has been achieved.

Lowering baselevel tends to produce a headward growth mode of development while the steepness of the slope changed the rapidity at which the network grew. Unfortunately, additional data are required to explore the effect of initial conditions further.

CHAPTER IV

TOWARD A MODEL OF NETWORK EVOLUTION

The remarkable similarity of the first-order stream length histograms at initiation and maximum extension demonstrated previously suggests regularity of network growth. Only for the initial network on a surface slope of 3.2 percent with no baselevel change is the histogram significantly different (more rectangular) and in this experiment the histogram approaches the characteristics of the histogram in the first experiment at maximum extension.

Even stronger evidence of regularity comes from the fact that the geometric mean length does not significantly change during the extension of the networks of data set 1. In order for this to occur, a first-order channel must grow to some limit and then bifurcate, therefore, being eliminated from the class of first-order streams. The marked regularity in the range of lengths may reflect a length at which the probability of bifurcation is maximized. As the length of a first-order channel increases, the probability of bifurcation increases. The bifurcation of the channel can occur anywhere along its length as it grows, but the stability of the geometric mean of first-order channel lengths suggests that there is only a small range of stream lengths at which the probability of bifurcation is a maximum.

The identification of a probability distribution for channel bifurcation is not straightforward. Such a distribution would undoubtedly vary in both time and space. Time is a factor because it is inherent in the incremental growth of a particular channel and the rate of growth changes with respect to location in the basin. Changes in competition among sub-basins may also affect the shape of the drainage area and inhibit bifurcation.

In modelling network growth, the most important causative factor may well be competition for undissected watershed area. If so, data will be difficult to obtain because sub-basin boundaries shift continuously before incision finally limits the mobility of the divides.

Another modelling problem is the inherent regularity of many geomorphic variables which are used to describe the stream network. The network is a specific topologic figure (a rooted planar graph) on which an ordering scheme is imposed. Thus, network variables can exhibit a regularity based on the mathematics of the unique topologic figure. This chapter focuses on the evolution of selected geomorphic variables; several of which point to this inherent regularity.

Evolution of Selected Geomorphic Variables

The evolution of several stream number and stream length variables, which identify the different modes of growth or focus on the regularity of growth, will be examined in this section.

Stream Numbers

Horton (1945, p. 291) stated the following law: "The numbers of streams of different orders in a given drainage basin tend to approximate a geometric series in which the first term is unity and the ratio is the bifurcation ratio (R_b)." This law, called the law of stream numbers, has been tested and found satisfactory by a number of researchers.

It was Horton's (1945, p. 303) contention that this law of stream numbers was relatively insensitive to geologic differences between basins but that departures from a straight line on a semi-logarithmic graph may, in general, be ascribed to the effects of within basin geologic controls. Many workers have tested this law under a variety of geologic and geomorphic conditions and have found both the geometric-series form and the bifurcation ratio to be very stable. This implies that the law is a result of a very basic cause.

However, some workers (Schumm, 1956, p. 603; Maxwell, 1960, p. 120) have identified a concavity in the semi-logarithmic relationship between stream order and stream number which implies that the law of stream numbers is not exact.

Shreve (1966, p. 18) on the other hand stated, that, "in the absence of geologic controls . . . , the population of natural channel networks is governed primarily by the tendency of erosional processes to produce arborescent networks and secondarily, or perhaps not at all, by local environmental factors." Shreve (1966, p. 18) further stated that: "this leads to the speculation that the law of stream numbers arises from the statistics of a large number of randomly merging stream channels in somewhat the same fashion that the law of perfect gases arises from the statistics of a large number of randomly colliding gas molecules." Milton (1965, p. 53) concluded that: " . . . the law of stream numbers is simply a statistical probability function that automatically follows the definition of order. It is basically not a geomorphic law, but an abstract law that must apply equally well to any branching system. The writer has in fact found that (the law of stream numbers) can be fitted to data from a plum tree . . . ."

Conclusions about the law of stream numbers have been based on data collected from basins which have evolved over a long period of time. Hence, the network is relatively stable within the basin it occupies; and the law of stream numbers is usually applied to a fully developed drainage pattern. In this experimental study the network has initiated on an undissected surface. Thus, changes in stream numbers can be observed as the network evolves from a very simple initial pattern. Such observations through time can identify changes, if any, in the law of stream numbers during network growth and these changes are related to the two growth models previously discussed.

To examine the change of stream numbers of both types of drainage network development (sets 1 and 2) with time, the development of Strahler first-order streams through initiation to maximum extension of the pattern was studied. First-order streams are used because it is by the formation of them that the network grows.

Strahler first-order streams are the fingertip stream segments from source to the first downstream bifurcation (Strahler, 1952, p. 1120). They are, therefore, equivalent to exterior links defined by Shreve (1967).

A plot of first-order stream frequency for all networks mapped during extension is shown in Figure 4.1. The increase of first-order streams is basically nonlinear with a decreasing number of streams added as time progresses. These trends are actually made up of two different data subsets. For example, for the data generated on the initial slope of 0.75 percent with baselevel change (set 1), five networks were recorded as the system initially grew (set 1, subset 1). Five more networks were mapped at maximum extension for a particular baselevel (set 1, subset 2). Because of these differences two linear regression equations were used to describe the relations.

The slope of the regression lines for the initially developing networks without baselevel change (subset 1 data) is greater than the slope of the line for the data at maximum network development (subset 2 data) for both experiments. This difference in the regression coefficients is significant at the one percent level. Thus, there is a rapid early development of first-order stream segments, but this is significantly reduced with time.

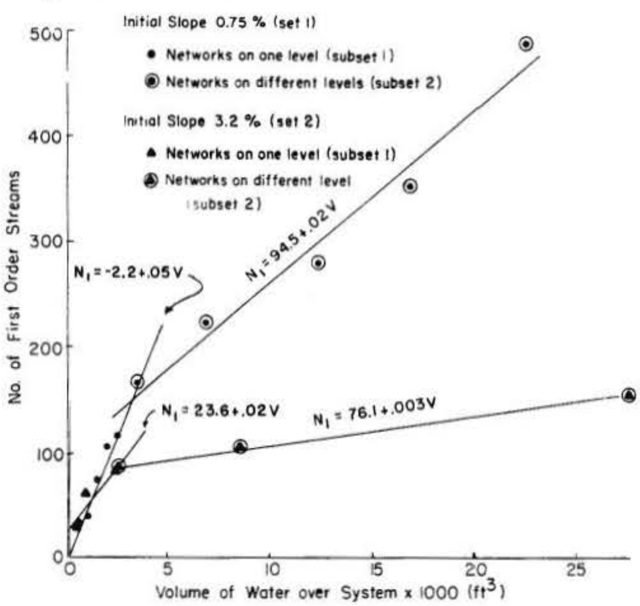

Fig. 4.1. Changes in the number of Strahler first-order streams formed during development of the pattern to maximum extension. Time is indexed by volume of water over the system.

During the initial rapid development of first-order channels, the rate of initiation of new channels is statistically the same for both experiments. This is shown by a t-test of the regression coefficients, at the one percent level.

However, as the network continues to grow into the basin, the rate at which channels are added differs for the two experiments (Fig. 4.1). In set 1 first-order streams are added at a faster rate so that by maximum extension many more first-order streams are present.

The growth of first-order streams is similar to that observed for stream lengths or drainage density (Fig. 3.1). Fewer first-order streams developed on the initial slope of 3.2 percent (set 2 data). This data set has already been characterized by being "Hortonian" in its mode of growth. The initial development in this experiment was the "blocking out" of large portions of the watershed by long first-order streams. The general "blocking out" of the network on the steeper initial slope seems to provide less opportunity for development of small exterior links.

Figure 4.2 shows a comparison between two subbasins for both initial conditions at equal times. The network on the steeper initial slope has developed longer first-order streams. The lower initial slope has shorter first-order channels, but the number of streams continues to increase as the network grows. First-order channels in the second experiment are longer and occupy more territory than similar channels on the lower initial slope. This certainly influences the competition for available area. The differences in the manner of network development must have an effect on the growth of new streams within the network, but the exact nature of this influence is undetermined.

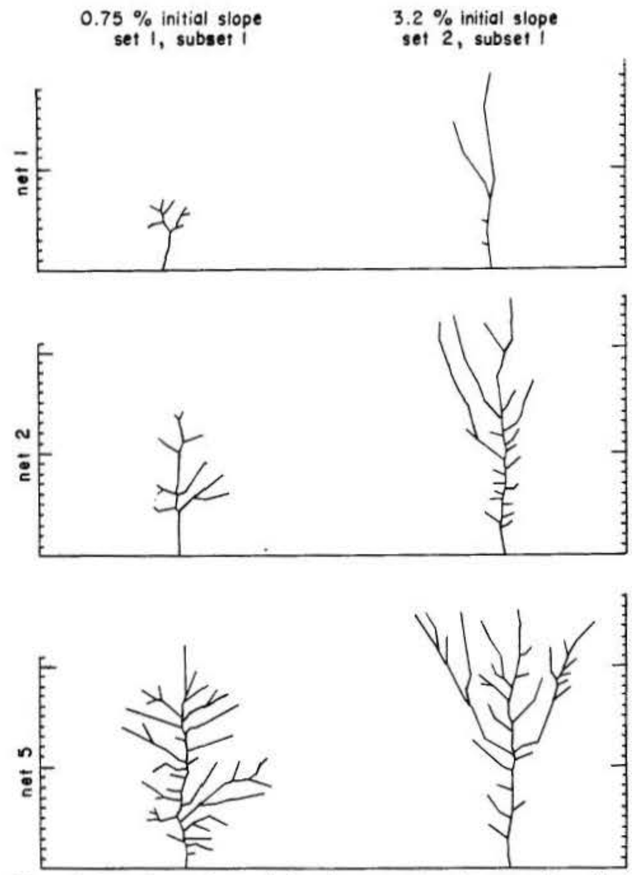

Fig. 4.2. Examples of drainage network growth. Networks are shown at equivalent times in the experiment to show differences in the patterns.

To show changes in stream numbers during the initial development of a network the number of Strahler-order streams are plotted on semi-logarithmic paper for each network. In order to provide more detail, data from four sub-basins in network 1 (Fig. 4.3) were plotted for each succeeding stage of development (Fig. 4.4). Because the network is actively growing headward the number of first-order streams increases for each data set. Thus, time can be thought of as increasing along to the y-axis with increasing numbers of first-order streams. Each line (an individual network) represents a time slice at two hour intervals.

First-order streams increase with time along the Y-axis (Fig. 4.4). However, the increase of first-order streams does not increase the number of second-

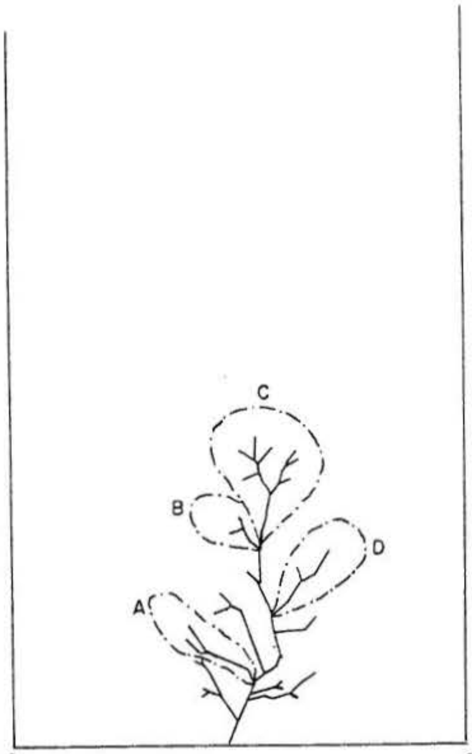

Fig. 4.3. Sub-basins from experiment 1 (set 1) used in the analysis of stream numbers.

order streams until there are 7 first-order streams. Between the development of 7 and about 12 first-order streams, only two second-order streams formed. This increase of first-order streams until eventually an additional second-order stream is formed continues, although with increasing numbers of first-order streams the tendency becomes less distinct.

The higher order streams also show this development. For example, between 2 and 11 second-order streams are added before an additional third-order stream formed (Fig. 4.4). This process produces lines on Figure 4.4 that are not straight, and probably explains the deviation from Horton's law of stream numbers noted by Schumm (1956, p. 603) and Maxwell (1960, p. 12).

With such a sequence of growth the bifurcation ratio between one order and the next ($R_{b_{i/i+1}}$) must undoubtedly vary.

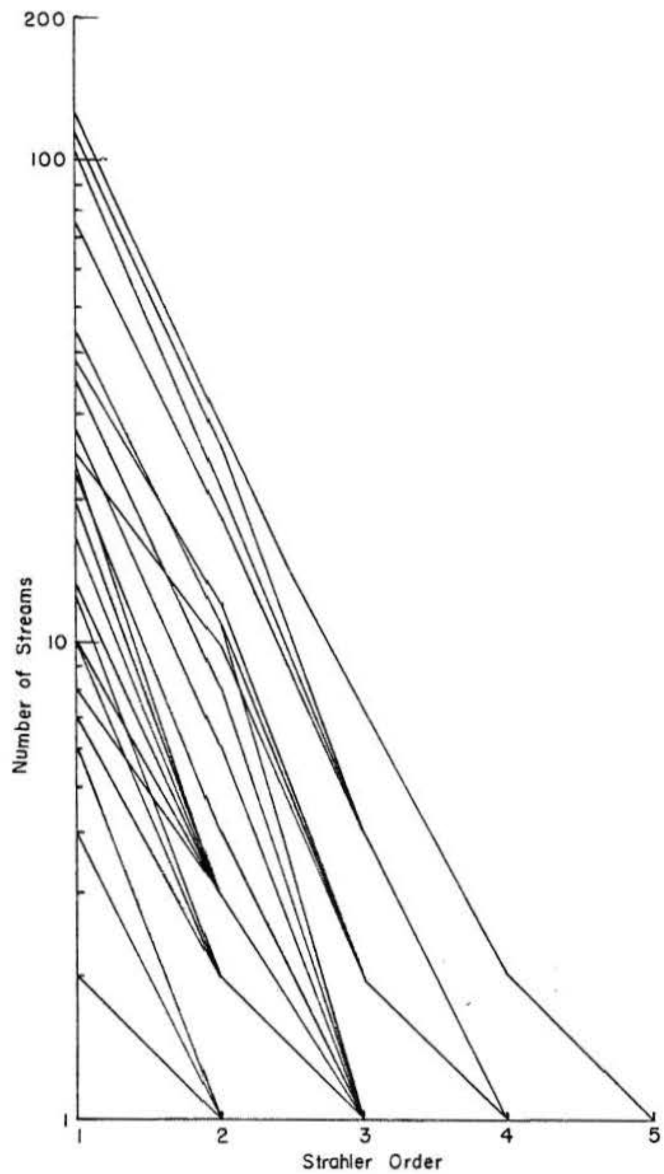

Fig. 4.4. Number of Streams for each Strahler order. Basins used include both sub-basins and total basins in order to show changes through time (set 1, subset 1).

Plotting bifurcation ratios for data from Table 4.1 and 4.2 yields ratios which do indeed change dramatically but in a regular pattern (Fig. 4.5). If the lines displayed in Figure 4.4 are numbered consecutively, a time index is obtained, and this is used as the X-axis in Figure 4.5. The numbers at the top of the plot give the number of second and third order streams or, in other words, the denominator of the bifurcation ratio plotted for that particular zone in the figure. There is an increase in the bifurcation ratio within each of these zones indicating a continued increase in the number of lower order streams without a change in the denominator of the bifurcation ratio. The oscillation of the bifurcation ratio decreases, as the drainage system expands or becomes older. Finally the ratio becomes relatively constant, a condition noted by many investigators.

Table 4.1. Number of Strahler order streams for networks during initial development on one baselevel

Set 1, Subset 1
(initial slope of 0.75 percent)

Network	Number of Strahler Streams 1	2	3	4	5
1	25	10	2	1	-
2	38	12	2	1	-
3	74	18	4	1	-
4	104	21	4	1	-
5	114	26	5	1	-

Set 2, Subset 1
(initial slope of 3.2 percent)

Network	1	2	3	4	5
1	24	5	1	-	-
2	64	13	4	1	-
3	81	22	7	1	-

Table 4.2. Summary of number of Strahler order streams for sub-basins shown in Figure 4.3.

Network (Set 1, Subset 1)	Sub-basin	Number of Strahler Streams Order 1	Order 2	Order 3
1	A	2	1	
	B	2	1	
	C	7	2	1
	D	2	1	
2	A	6	1	
	B	4	1	
	C	10	3	1
	D	8	3	1
3	A	10	3	1
	B	10	2	1
	C	27	6	1
	D	13	3	1
4	A	16	3	1
	B	12	2	1
	C	34	8	1
	D	21	4	1
5	A	19	3	1
	B	12	2	1
	C	45	11	1
	D	22	4	1

Increases of the R_b within one zone indicate that the probabilities of branching to form a i + 1 order stream by an i^{th} order stream is not always 0.5 as suggested by Schiedegger (1966) instead the probability of forming an i + 1 channel decreases from 1.00 until the next transition is reached, and then it jumps to a new high value and begins a slow decrease. This oscillation of probabilities would be just the inverse of the bifurcation ratio plot shown in Figure 4.5.

Eyles (1968) described the upward concavity in a plot of stream numbers versus order in basins in Malaysia and felt that it could be taken as evidence of recent rejuvenation, which disproportionately increased the numbers of lower order streams (particularly the first-order). In such a case the bifurcation ratio will be inversely related to stream order. Smart (1968, p. 25) also found in working with random walk models that the data from stream systems in the western United States fit the random model except for

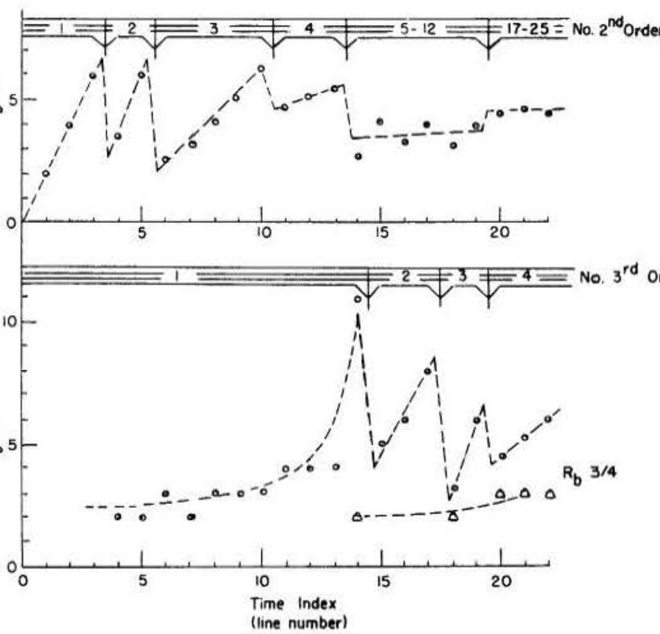

Fig. 4.5. Changes in bifurcation ratio between one order and the next higher order during early stages of network development. Lines from Figure 4.4 were numbered consecutively from the origin and used as a time index.

a systematic deviation from randomness provided by an excess of lower order streams, which gave greater values for the bifurcation ratio than those predicted by the model. Such deviations were described as "probably due to geologic controls." It is unknown if such a deviation is a result of rejuvenation, but the results of the experimental study demonstrate that it is characteristic of a growing network.

The initial oscillation does not detract from the observations made by many that the bifurcation ratio is particularly stable. Such observations were made on networks which were not undergoing rapid change. As noted here, this oscillation is quickly damped as the network grows larger and in fact at maximum extension the stream frequency-order plots are straight (Fig. 4.6) and show stability of the bifurcation ratio.

Exterior Link Lengths

The mean length of exterior links (first-order streams) is not significantly different through time in the first experiment. However, in the second experiment there is a statistically significant decrease in the mean length of the exterior links with time. To examine these exterior link lengths, they are separated into tributary source (TS) links and source links (S) defined previously (Mock, 1972). The data (Table 4.3) for the second experiment (set 2, subset 1) on the steeper initial surface show that the decrease in the geometric mean length of exterior links results primarily from a decrease in length of S-type links. TS-type links have a nearly stable mean length. A t-test identifies no difference among the mean length of TS links between networks 1, 2, and 3 at the 95 percent level. A t-test yields a statistically significant difference among the mean lengths of S-type links in the same three networks at the 95 percent level.

The changes in S and TS exterior links can be shown by smoothing the histograms of length using the equation for the lognormal distribution (Aitchison and Brown, 1957, p. 8):

$$f(x) = \frac{1}{x\,\sigma\,\sqrt{2}} \exp\left(-\tfrac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right) \tag{4.3}$$

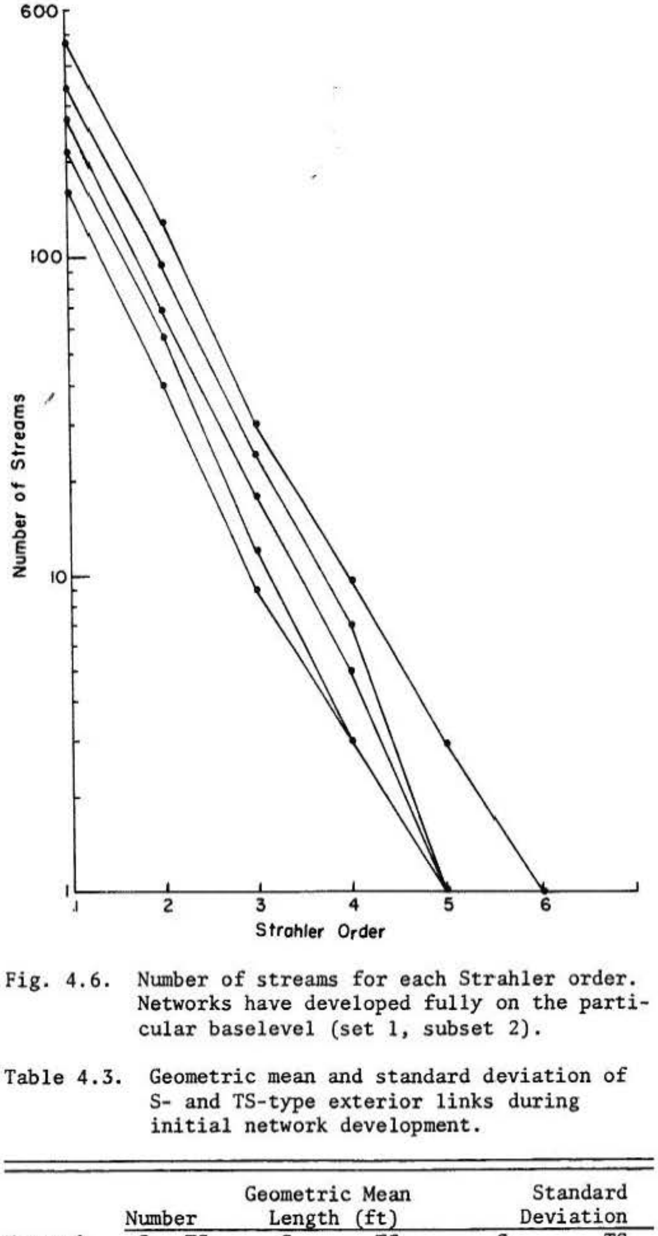

Fig. 4.6. Number of streams for each Strahler order. Networks have developed fully on the particular baselevel (set 1, subset 2).

Table 4.3. Geometric mean and standard deviation of S- and TS-type exterior links during initial network development.

Network	Number S	Number TS	Geometric Mean Length (ft) S	Geometric Mean Length (ft) TS	Standard Deviation S	Standard Deviation TS
Set 1, Subset 1						
1	20	5	1.01	1.65	1.97	1.70
2	25	13	0.79	1.89	2.10	1.95
3	36	38	1.33	1.76	1.64	1.99
4	42	62	1.39	1.46	1.84	1.96
5	52	62	1.53	1.46	1.82	1.90
Set 2, Subset 1						
1	10	14	5.91	2.23	1.84	2.27
2	26	38	3.53	2.94	2.02	1.94
3	44	37	2.96	3.17	1.67	1.97

Using the maximum likelihood estimators of the mean and variance, the frequency curve for each network can be calculated. A dramatic shift of the S-type link length curve from larger values to smaller values (shift to the left) is shown (Fig. 4.7). The stability of the TS-type link length distribution is evident for these three networks. The fact that S-type links are longer initially and that they shorten with time suggests the importance of this link type in the "blocking out" stage of channel development on the steeper initial slope. As these initially long S-type links develop tributaries, their lengths are shortened.

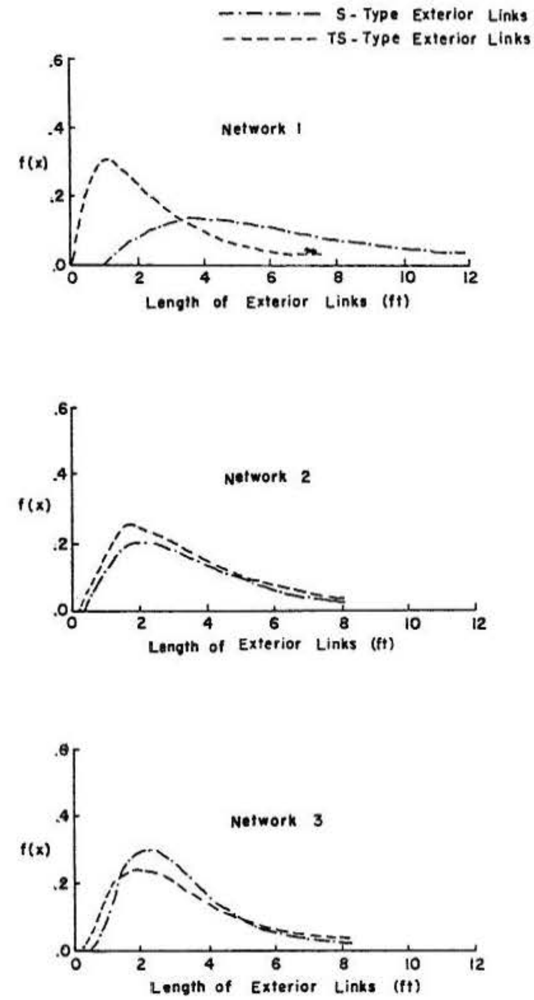

Fig. 4.7. Frequency curves for exterior link lengths using the maximum likelihood estimators for the mean and variance. The log normal distribution is used. Data are from set 2, subset 1 with an initial slope of 3.2 percent.

The reason for the stable nature of the TS-type link distribution through time is difficult to ascertain. Schumm (1956, p. 608) defined interbasin areas as roughly triangular areas which have not developed a drainage channel but which drain directly into a higher-order channel. If single channels develop in these interbasin areas, they would be TS-type links. Thus, channelization of interbasin areas late in network growth would tend to reduce the mean of the length disdribution of TS-type links with time as smaller link lengths fill these small interbasin areas. Such does not appear to be the case.

The S-type links that initially block out the basin divide sub-areas for future dissection by TS-type streams. A regularity in spacing of streams produces a proportionate number of both short and long TS-type links to develop which allows the distribution of link lengths to maintain a nearly constant mean and variance through time. This regularity suggests a basic causal factor influencing link length such as the eroding material (the geology).

Computer Simulation Models

The simulation of stream networks was initiated by Leopold and Langbein (1962). They proposed a random walk model in which the network initiated at the heads of first order streams (sources) and grew in unit steps toward the outlet. The rules of growth allowed growth to the left, right or towards the outlet with equal probabilities. Growth back towards the sources was not allowed. If channels met, only one channel continued growth from the intersection. A secondary model, similar to this one, in which exterior links could be initiated at random locations on the gridded watershed, was also proposed in the same paper. These models were programmed for the computer and compared with natural drainage systems (Schenck, 1963; Smart et al, 1967).

A headward growth model was proposed later (Howard, 1971; Smart and Moruzzi, 1971 a, b). These headward growth models characterize headward growth by beginning at the basin outlet and developing into the basin and, therefore, more accurately reflect an actual growth model. Attempts to model capture of drainage area from above as growth continues were attempted in this headward growth model.

Both these types of models have been compared with natural drainage networks. With probabilities of growth equal in each allowed direction of growth, it has been assumed that the computer model reflects the development of a drainage system on homogeneous lithology. Comparisons of the simulated networks with natural networks have shown a great many similarities. These similarities have been used both to justify the computer model as an adequate simulator of the real world and to hypothesize that network development on homogeneous material results from equal probabilities of growth or random growth. Such reasoning appears circular.

Howard (1971) suggested that the nearly equivalent results obtained between the simulated and natural networks may be superficial. That is, the simulation methods are successful because they produce the topologic properties of natural networks. As has been shown in this experimental data the number of streams of a particular type and the geomorphic statistics generated from them (e.g., the bifurcation ratio) does not show substantial differences from the topologic theory developed by Shreve (1966, 1967).

It appears, therefore, that the rules used in the simulated networks to obtain the topologic figure similar to the natural drainage pattern, results in similar stream or link numbers. That is, the reproduction of the specific topologic figure (the rooted planar graph), which describes the stream network, results in similar values of variables. This similarity may not, however, be geomorphically significant in terms of identifying growth characteristics in actual streams.

Problems with the stream lengths also exist in these computer simulations. It has been implied that in natural basins drainage density changes with rock type (Hadley and Schumm, 1961; Carlston, 1963). Such changes are not an immediate result of the simulation models. As drainage density changes, the length distribution of exterior and interior links must also change although the ratio of mean exterior length to mean interior length may not. Simulations have relied heavily on these ratios in comparing simulation output with natural drainages and may not have identified significant differences.

Simulation model networks have been identified as expressing random growth and natural networks that resemble these simulations are said to exhibit random growth. Such terminology is, indeed, unfortunate because it focused further work on the random component of drainage development rather than on causal factors of growth. This focus was maintained even though simulation techniques used have a direct functional relation with drainage density and its inverse--the constant of channel maintenance (Schumm, 1956, p. 607). All simulations produced to date use a matrix or grid coordinate scheme within which to grow. Each grid element represents a unit length of possible growth. In the Leopold-Langbein model (1962, p. A 15) the distance (D) or length of a stream from initiation to joining with another stream was given, from the statistical model called the "gambler's ruin," as a minimum limit of the first power of the separation distance (A) and a maximum limit of the square of the separation distance. Thus, the length of an individual channel (D) has a minimum and maximum limit which is dependent on separation or cell size and the actual length of an individual link is, therefore, a function of the cell size in the matrix.

The unit length of a cell has a direct functional relation to the constant of channel maintenance (CCM) which changes with the changes in probabilities given for growth in each of the allowed directions. Thus, the simulation models have a built-in deterministic component. This component has not been adequately identified or analyzed, but it is probably related to geologic and climatic influences in the prototype.

Simulation models have been based and analyzed on the topology of the stream network. Mature simulated networks, which have filled the available area, are compared with assumed mature networks in the field. There is no way to change external variables in the simulations which alter growth because of differences in geology, climate, or changes in baselevel except by unknown changes in the probabilities of direction and amount of growth or by altering cell size. In addition, there is no method to maintain the "memory" of the system growth to these external changes in variables nor alter this "memory" with time.

It has been shown that there are substantial differences in growth depending on initial conditions. These differences have been related to two different growth models. Such growth mode changes cannot be effectively modeled in the random walk simulation schemes to date.

External variables such as relief, baselevel change, climate, and geology also effectively alter the growth of natural networks. Yet, these variables are not found in the simulation models as driving variables influencing pattern growth. For example, with a change in baselevel, the network is rejuvenated. The total basin may not be dissected because the network growth depends on the relief available from the baselevel change. Computer models developed to this time do not consider the driving forceof a given relief.

Identifying regularity in network growth is made difficult by the many geomorphic variables, which have an inherent regularity resulting from the mathematics of the network topology. This was shown earlier in this chapter by variables associated with stream numbers. However, there is a need to identify the response of network growth to external variables and the network regularity produced by them. Admittedly, network growth has a random component but any modelling effort must include a degree of deterministic behavior.

<u>Summary</u>

Lengths of first-order streams are similar through maximum extension in the first experiment. This similarity is seen in both the length histograms and the geometric mean lengths of these streams. Such similarity suggests a regularity in network growth.

Identifying regularity in the growth of a network is difficult because of the inherent regularity produced by the topology of the network. Many variables associated with stream numbers seem to contain this inherent regularity. Although the number of streams changes with time and between experiments, the relative frequency of occurrence of stream number variable remaining stable is the bifurcation ratio. This stable variable showed some fluctuations during initial network development but even these changes can be ascribed to the topology of the network.

Further work needs to be done to identify network variables which contain a regularity induced by underlying causative factors. An example of such a variable seems to be the first-order stream lengths in the second experiment. A decrease in first-order stream (exterior link) lengths was seen in this second experiment. A decrease in first-order stream (exterior link) lengths was seen in this second experiment. Separating these exterior links into S and TS links, it was shown that the TS type link lengths were stable during network growth. This is somewhat surprising because it is the TS links that primarily fill in the skeletal network. This result indicates a regularity in sub-basin development. This regularity may well be dependent on several underlying causative factors such as geology or climate. These factors would influence the competition among sub-basins for drainage area.

Modelling drainage network growth must account for these causative factors. Simulations to date have used random walk techniques almost exclusively. Such models have a deterministic component related to the cell size of the matrix and the assigned probabilities of branching. Little work has been done to evaluate these factors. The emphasis has been on the random component. Thus, the effect on the network of changes in external variables such as geology or climate cannot be evaluated.

CHAPTER V

ABSTRACTION

It was demonstrated in Chapter IV that rate of network growth reaches a maximum and then decreases to near zero. During decrease in growth, many channels are static or remain unchanged, but as extension progresses, channels are abstracted at an increasingly higher rate. Thus, the processes defined by Glock overlap from one category into another. Nevertheless, at maximum extension the initiation and growth of new channels is reduced to near zero, and abstraction becomes the dominant process.

During experiment 1, maximum extension was achieved too late in the experimental season for the experiment to continue, but during the second experiment, erosion was continued at a constant baselevel after maximum extension (set 2, subset 3). Data set 2, subset 3 has four networks (Appendix A). Extension continued to network 2, and it represents maximum extension whereas the final two networks (3 and 4) are representative of abstraction. This chapter will focus, therefore, on these two networks.

Stream Numbers

During abstraction links are lost. This loss of exterior stream links through time is shown in Figure 5.1. After maximum extension, the decline in exterior links is rapid with a 57 percent decrease between maximum extension (network 2) and network 4. By definition the number of interior links in a network is one less than the number of exterior links; therefore, the loss of exterior links reflects a loss of interior links.

The number of streams in each Strahler order are given in Table 5.1 and data for the last three networks are plotted on Figure 5.2. These three lines illustrate the change in channel frequency from maximum extension into abstraction. The lines are fairly straight, although the decrease to a fourth order basin at network 4 seemed required to straighten the line. Except for these variations the lines appear straight and almost parallel.

Abstraction of exterior links will not continue indefinitely. As the system continues to evolve, the rate of link loss will decline until only a skeletal network remains. This may be stable for a long time unless external variables such as the precipitation rate or baselevel are changed.

The downward shift of the lines of Figure 5.2 indicates a regularity in channels lost and suggests that streams are not lost selectively. Table 5.2 shows the number of each exterior link type for the abstracting network. Of the exterior links abstracted between networks 2 and 3, 50 percent are S-type and 50 percent are TS-type. Between networks 3 and 4, 42 percent of the exterior links abstracted are S-type links. Hence, there appears little difference in the type of link cost.

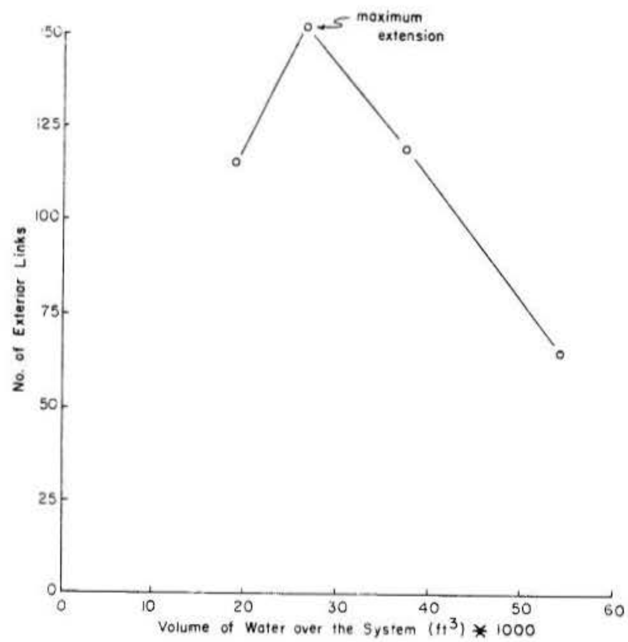

Fig. 5.1. Changes in the number of exterior links (Strahler first-order streams) through time for a network evolving through maximum extension into abstraction. Time is indexed by volume of water over the basin. Data are from set 2, subset 3.

Table 5.1. Number of Strahler streams for set 2, subset 3

Network	Strahler Order 1	2	3	4	5	R_b[1]
1	115	28	8	2	1	3.36
2	152	39	10	3	1	3.53
3	117	30	8	2	1	3.40
4	65	14	5	1	-	3.88

[1]The bifurcation ratio defined as the best fit line without the requirement that it pass through the endpoint.

Abstraction begins during extension near the basin outlet (Table 3.2). As evolution continues and abstraction becomes the dominant process, the zone of abstraction extends from the internal or older parts of the basin. This migration of abstraction is shown by the evolution of networks 2, 3 and 4 (Appendix A, set 2, subset 3).

A few additional channels are added during abstraction. Extension continued by the addition of

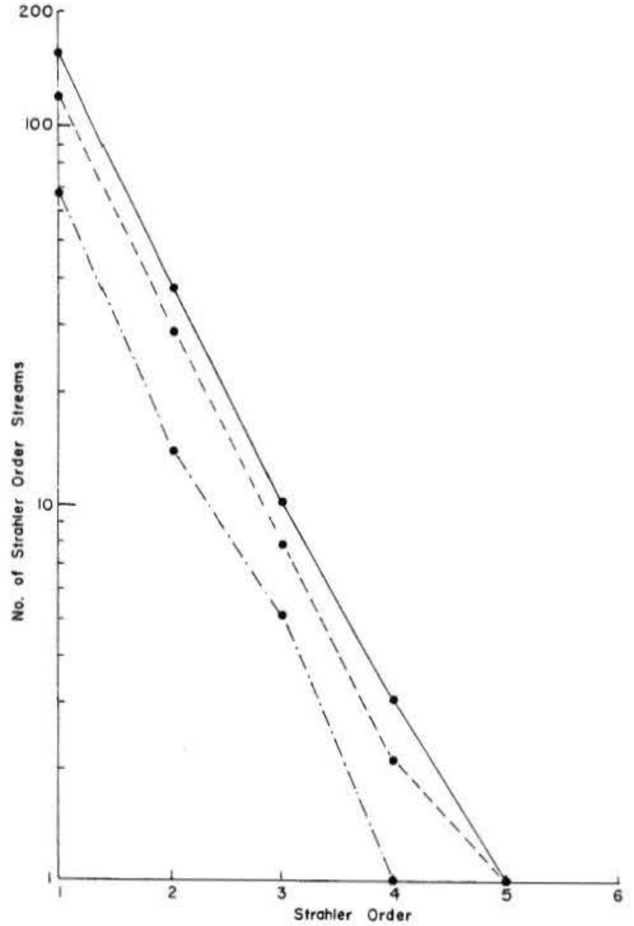

Fig. 5.2. Number of streams for each Strahler order for an abstracting stream system. Curves for successive networks approach the origin as additional streams are lost through time. Data are from set 2, subset 3.

eight exterior links between network 2 to 3. This represents seven percent of the total exterior links, and it is not significant in view of the fact that 23 percent of the channels from network 2 were abstracted. In network 3 these additions occurred equally around the perimeter and internally near the main channel. In network 4 only four channels, or 6 percent, were added.

Stream Lengths

Two trends of Strahler-order stream lengths are shown in Table 5.3 for the abstracting system. One is the overall tendency for an increase in mean length of first-order channels through time. Because of the loss of stream numbers, this increase in stream lengths is to be expected. Second, is the reduction of basin order as the system abstracts. This decrease of the highest order stream tends to increase the mean length of the new highest order stream.

A t-test was used to identify differences in the geometric mean lengths of S and TS type links for each of the three networks in the abstracting system (Table 5.4). At the 5 percent level the TS-type links were significantly longer than the S-type links. Thus, the TS links drain large segments of the internal basin area. These TS links become important conveyors of water from the large areas that remain within the skeletal stream system. The S-type links remain short and are found primarily in the high relief areas around the basin perimeter.

Table 5.2. Number of links in an abstracting system (set 2, subset 3)

Network	No. of Exterior Links	No. of S-Type Links	No. of TS-Type Links	% Exterior Links That are S-Type
1	115	56	59	48.7
2	152	78	74	51.3
3	117	60	57	51.3
4	65	28	37	43.1

During abstraction the mean of interior link lengths shifts to larger values with time (Table 5.5). The increase was shown to be significant at the 5 percent level by analysis of variance. The loss of channels (primarily exterior links) produces fewer bifurcations and results in longer interior links. There is, therefore, a close relationship between number of channels and the average length of channel for both exterior and interior links.

Changes in the Network Pattern

Abstraction has been characterized by the deletion of channel segments in the network, accompanying an overall loss of relief in the basin. This reduction in relief is the result of the continued process of rainsplash wearing down the divides and the lateral migration of larger streams.

The continued lowering of divides by rainsplash throughout the basin evolution, produced during abstraction some divides that were little higher than the channels. This allowed dramatic shifting of streams across these divides to join neighboring tributaries. Most of this shifting occurred near junctions of larger tributaries, where divides had less relief, rather than near the perimeter of the network. The shift did not appear to be the result of aggradation in the channel but rather, to the lowering of the divide.

Lateral migration of major tributaries was also a major process at maximum extension and early abstraction. The main channel was nearly straight shortly after baselevel lowering, but sinuosity increased, as evolution continued on a particular baselevel, though maximum extension. By the time abstraction was a dominant process, this increased sinuosity and the downstream migration of the meanders had planned off much of the surrounding material to form large valleys. The lack of resistance of the eroded material was undoubtedly a factor in the magnitude of this process. This lateral migration also contributed to the shifting of channels by providing large valley areas with little difference in relief. In some cases the continued reduction of a divide between two streams resulted in an upstream migration of the stream junction.

Several examples of stream junction shift are shown for Strahler fourth-order tributaries at junctions with the main channel (Figure 5.3). Shown is a reach of the main channel profile for the four networks in the subset. Both large tributaries (Appendix A, set 2, subset 3, No. 1 and 2) show a migration downstream, and then a migration upstream. It will be recalled that network 2 represents maximum extension. Thus, the migration of the tributaries is downstream during extension and upstream during abstraction. Note that the variable mapped on the X-axis uses distance along the main channel. Because sinuosity of the main channel decreases during abstraction (networks 3 and 4), the tendency would befor a junction to migrate

Table 5.3. Geometric mean length of Strahler order streams (set 2, subset 3)

Strahler Order	Network 1 n	Network 1 Geomet. Mean	Network 1 Stand. Dev.	Network 2 n	Network 2 Geomet. Mean	Network 2 Stand. Dev.	Network 3 n	Network 3 Geomet. Mean	Network 3 Stand. Dev.	Network 4 n	Network 4 Geomet. Mean	Network 4 Stand. Dev.
1	115	2.16	1.81	152	1.52	2.02	117	1.82	1.86	65	2.90	2.13
2	28	3.70	2.51	39	2.00	2.67	30	3.90	2.37	14	6.84	1.88
3	8	8.92	2.91	10	10.78	1.85	8	12.91	1.65	5	9.87	1.69
4	2	10.64	-	2	7.25	-	2	8.78	-	1	30.76	-
5	1	16.53	-	1	24.69	-	1	15.67	-	-	-	-

Table 5.4. Statistical summary of exterior links for set 2, subset 3

Network	Total Exterior Links n	Total Exterior Links Geomet. Mean	Total Exterior Links Stand. Dev.	S-Type Links n	S-Type Links Geomet. Mean	S-Type Links Stand. Dev.	TS-Type Links n	TS-Type Links Geomet. Mean	TS-Type Links Stand. Dev.
1	115	2.16	1.81	56	1.62	1.58	59	2.84	1.79
2	152	1.52	2.02	78	1.15	1.81	74	2.05	1.99
3	117	1.82	1.86	60	1.51	1.73	57	2.23	1.88
4	65	2.90	2.13	28	1.91	1.72	37	3.97	2.11

Table 5.5. Statistical summary of interior link lengths. Data transformed to natural logarithms.

Set 2, Subset 3

Network	N	Geometric Mean (ft)	Standard Deviation	l_e/l_i
1	114	1.85	2.28	1.17
2	151	1.34	2.59	1.13
3	116	1.78	2.49	1.02
4	64	2.19	2.36	1.32

downstream in this graph if the junction actually remained in the same position on the watershed. The actual migration of the junction upstream overcomes this tendency on the graph.

Such migration of junction results in the tendency for entrance angles to decrease during extension (Schumm, 1954, p. 31, 39; Horton, 1945). Schumm (1954) suggested entrance angles increased during later stages of evolution due to lateral migration planning off the divides between stream and allowing the tributary junction to migrate upstream. Lubowe (1964) found entrance angles increased for higher order channels which also suggests that entrance angles increase during later stages of evolution as shown here.

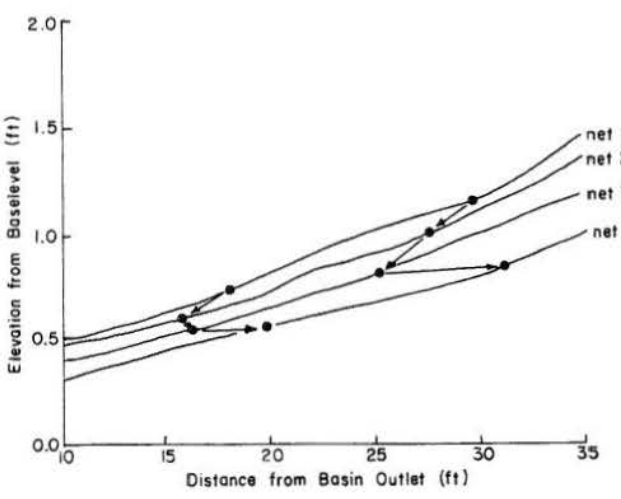

Fig. 5.3. Changes through time in the position of the junction of two strahler fourth-order tributaries with the main channel. Data are from set 2, subset 3.

Summary

As network links are abstracted, the topology of the network remains fairly stable. That is, the law of stream numbers defined by Horton (1945) persists although loss of channels modifies the straight line relation. This implies that S and TS type exterior links are not abstracted preferentially and this is reflected in the data.

Through the loss of channels the length of those interior and exterior links left in the network are increased.

There is a definite inverse relation between the number of exterior links and the geometric mean link length. TS-type exterior links are maintained to drain large areas internal to the network and, therefore, tend to become longer. S-type exterior links are found primarily at the periphery of the network or the basin perimeter. The fixed walls of the watershed boundary do not allow the ground surface to be lowered and the result is a zone around the perimeter, which has a higher relief than the internal area of the basin. This zone of higher relief contributes to the maintenance of short S-type exterior links.

Because the mean length of exterior links increases faster than the interior mean length (primarily due to the contribution from TS-type exterior links), the mean length of interior links is always less than the exterior link mean length.

There are some additional links produced during abstraction, but it is a minor process. The additions occur primarily near the main channel and near the outlet. Large portions of the interior of the network are without channels, and some links are established to drain these areas. As link addition and shifting occurs near the main channel, the development of these channels also helps to lower the mean length of interior links along the profile.

Although the categories of growth used here and identifiable by Glock (1931) imply that extension occurs up to maximum extension and abstraction occurs after maximum extension, there is an overlap in the processes. Abstraction begins early in extension and becomes more dominant as maximum extension is reached. Extension, on the other hand, continues well into abstraction although the development of new channels substantially reduced as abstraction continues. Thus, maximum extension appears to represent a transition at which the major process is converted from extension to abstraction.

Entrance angles at larger order stream junctions appear to decrease during extension and increase during abstraction. The increase in junction angle is produced by lowering of the divide areas which allows the upstream migration of the stream junction. Divide lowering, which was a major process in abstraction, occurred by wearing down the divides through rainsplash and overland flow and lateral erosion initiated by the lateral migration of the larger streams. Lateral migration became an effective agent of erosion near maximum extension. As abstraction continued, the main channel decreased in sinuosity.

CHAPTER VI

SEDIMENT YIELDS

Changes in sediment yields through the evolution of the drainage basins are examined in this chapter. Table 6.1 summarizes the time and relief differences for the basins at each baselevel during the first experiment (set 1). This table is oriented to the continuous data rather than the discrete data found in Table 2.4 used to summarize the experiments. Table 6.1 is organized in terms of the baselevel lowerings which have an important impact on the sediment yield of the basin. The second experiment (data set 2) conducted on the steeper initial slope involved four baselevel changes (Table 6.2).

$$S = 72.36\ V^{-.86} \tag{6.1}$$

where: S = sediment yield in tons/hr

V = volume of water over the system (ft^3)

As is the case with most sediment data there is a large scatter about this mean line (correlation coefficient of - .86), but the overall trend from very high yields, as erosion begins near the outlet, to a decrease in sediment yield, as the network ceases to grow at this baselevel is evident. The minimum sediment yield toward the end of the run is due to rainsplash which continues at a constant rate after most of the channel erosion has ceased.

Table 6.1. Summary of Baselevel Changes for Set 1 Data

Baselevel Number	Volume of Water Over the System for Baselevel (ft^3)	Accumulated Volume of Water Over The System (ft^3)	Relief from Horizontal (ft)	Network (Set 1, Subset 2) Mapped
1	3528	3528	0.985	1
2	3276	6804	1.280	2
3	5292	12096	1.580	3
4	2268	14364	1.902	None
5	2016	16380	2.186	4
6	5418	21798	3.069	5

Table 6.2. Summary of Baselevel Changes for Set 2 Data

Baselevel Number	Volume of Water Over the System for Baselevel (ft^3)	Accumulated Volume of Water Over the System (ft^3)	Relief From Horizontal (ft)	Network Mapped
1	2520	2520	1.478	Set 2, subset 1 networks 1,2,3
2	5796	8316	1.744	Set 2, subset 2 network 2
3	5796	14112	2.688	none
4	3528	17640	2.324	none
5	36792	54432	2.559	Set 2, subset 3 all networks

Changes in Sediment Yield with Time

The five networks of set 1, subset 1 were obtained as the network initially developed on baseone. The flat, undissected surface was subjected to a baselevel lowering of 0.98 ft. from the horizontal and the initiation of the network commenced. The sediment yield for baselevel one is shown in Figure 6.1. The data show a marked exponential decay after baselevel lowering. The resulting regression equation is:

Figure 6.2 shows the changes in sediment yield during experiment 1 along with the associated baselevel changes. The plot is compressed in the X-direction and the exponential decay form of the plots is

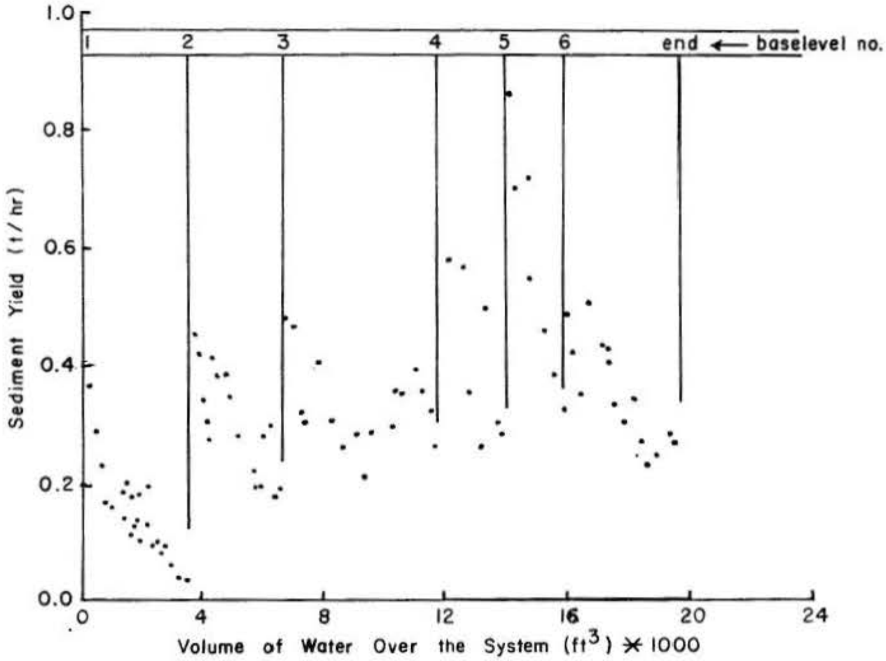

Fig. 6.2. Changes in sediment yield through time during experiment 1 (set 1). Changes in Baselevel are Indicated. Time is indexed by Volume of Water Over the System.

lost. For example, the data plotted from intiation to the first vertical line is the same data plotted in Figure 6.1. The numbered baselevels across the top of Figure 6.2 refer to the baselevel numbers given in Table 6.1. Again, this graph shows large scatter of the data. Trends are not easily identified because there is an insufficient number of data points given the variability inherent in the data. Although the data show much scatter the overall exponential decay after a baselevel lowering is evident.

If the trends following each baselevel lowering are ignored there is an increase of sediment yield with time. This occurs because first, after the initial baselevel lowering, none of the subsequent runs were of sufficient duration to permit sediment yield to decrease to the minimum value of the initial run. Second, with each increment of baselevel lowering the overall basin relief increased and, therefore, initial values of sediment yield are generally larger. A quantitative relation between basin relief and initial sediment yeilds is difficult to establish because of an inability to identify a set of sediment yield values that is homogeneous in time. That is, the sediment yield data collected between baselevel changes represents a long evolutionary process in geologic time, and the rapid change of sediment yields (Fig. 6.2) does not allow the grouping of values into a time unit comparable with data collected in the field.

Sediment yields for the run on baselevel 1 in the second experiment (set 2, subset 1) are shown in Figure 6.3. The least squares equation for the data is:

$$S = 0.55V^{-1.46} \quad (6.2)$$

Where: S = sediment yield in t/hr

V = volume of water over the system (ft^3)

A comparison of this equation with equation 6.1 from experiment 1 shows that the rapid decrease of sediment yield soon after initiation is not as pronounced during the second experiment with no baselevel change. Also, higher values are maintained through the latter part of the run in comparison with experiment 1. The more pronounced initial high of set 1 data reflects the effect of very high sediment yields related to the lowering in baselevel and knickpoint formation at the mouth of the basin. The basin was not subjected to a baselevel change before the run during experiment 2, and the sediment is produced by the development of channels which incised directly into the steeper surface. The network developed quickly over a large portion of the watershed under these conditions, but a large kickpoint did not form and initial sediment yields were low, Thus, the differences in sediment yield between the two experiments appear related to the changes in initial conditions. Baselevel change initially produces very high sediment yields as the kickpoint retreats from the basin mouth, but, as the network extends into the basin, the downstream channels store some sediment and, sediment yields are reduced to a lower value than during experiment 2.

In the second experiment with no baselevel alteration, the initial skeletal network incised directly into the watershed surface. During this process a series of small kickpoints developed in the basin interior. The skeletal network had a low efficiency of sediment transport to the outlet. This was revealed by small fan-shaped depositional areas that developed downstream from tributary junctions. Thus, initially sediment yields were not very high, but continued incision of the channels and an increase in sediment transport efficiency maintained higher sediment yields for a longer period during basin evolution. The internal growth of new channels and the rearrangement of streams, characteristic of Hortonian growth, may also tend to maintain sediment yields at higher values later in the network evolution.

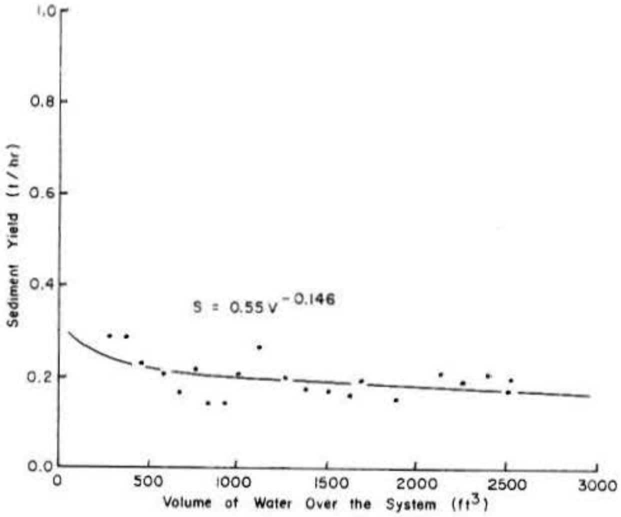

Fig. 6.3. Changes in sediment yield through time for Experiment with an Initial Slope of 3.2 Percent and no Change in Baselevel. Time is Indexed by Volume of Water Over the System and is Associated with The Networks From Set 2, Subset 1.

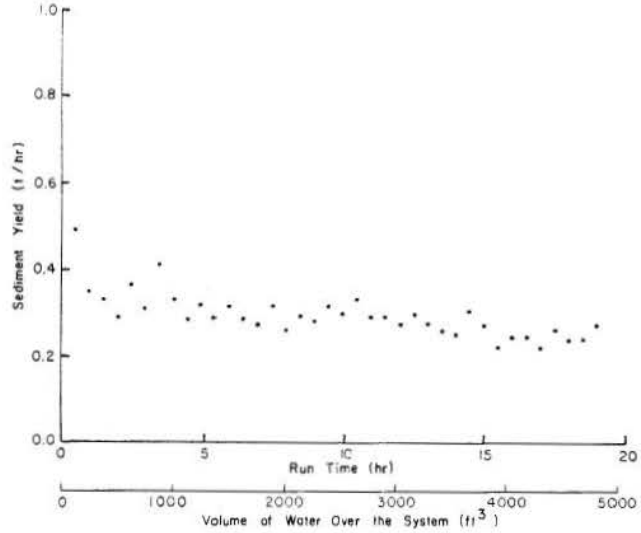

Fig. 6.4. Changes in sediment yield through time for experiment with an initial slope of 3.2 percent (set 2) on baselevel 2. Time is indexed by volume of water over the system.

Variability of Sediment Yield

Although the overall trend of sediment yield occur as an exponential decay, all of the data show great variability. This variability is so great that trends and relations between basin morphology and sediment yield are difficult to establish. Data from the second experiment, during which more samples were obtained, permit better identification of trends, but nevertheless, a high degree of variability is maintained. Large changes in sediment yield occur over short periods of time, during the experiments, even when water discharge is held constant.

In the field major sediment yield changes are assumed to result from climatic fluctuations and land use changes. However, the experiments when sources of variability were held constant, demonstrates that sediment yields normally maintain a high variance. In nature the added variability from land use and climatic fluctuations may make short term changes in sediment yield difficult to predict.

The sediment yield changes with time for baselevels 2, 3, and 4 (set2) respectively, are shown in Figures 6.4, 6.5, and 6.6 and a trend can be detected. As relief increases, the initial values are higher, the first secondary peak is higher and occur sooner. There is high variability in all the data sets after initial decay.

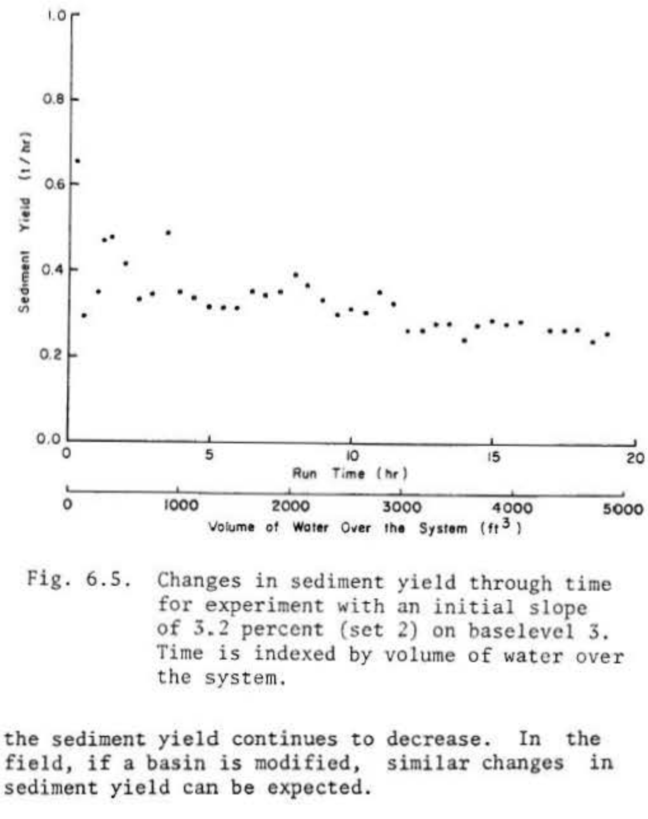

Fig. 6.5. Changes in sediment yield through time for experiment with an initial slope of 3.2 percent (set 2) on baselevel 3. Time is indexed by volume of water over the system.

The last baselevel in this experiment was maintained for a considerable time and this run shows both extension to maximum extension and then abstraction. The changes in sediment yield with time are shown in Figure 6.7. Maximum extension of the network is shown by a vertical arrow. Following lowering of baselevel (time zero) there is an initial exponential decay of sediment yield values. This is followed by an increase in sediment yield (or at least a higher variance), and then a further decrease. This sequence all takes place before maximum extension or while the network is still growing (Fig. 6.7). After maximum extension (Fig. 6.7) when abstraction is the dominant process, the sediment yield continues to decrease. In the field, if a basin is modified, similar changes in sediment yield can be expected.

For example, modification of drainage basins by urban development or mining could lead to a large increase in sediment yield followed by an exponential decay, as the system re-adjusts to the new situation. The large variability within the data creates a problem of identifying the specific values of sediment yield for a basin. This variability is greatest shortly after the basin has undergone modification. Unfortunately, it is at this time that the identification

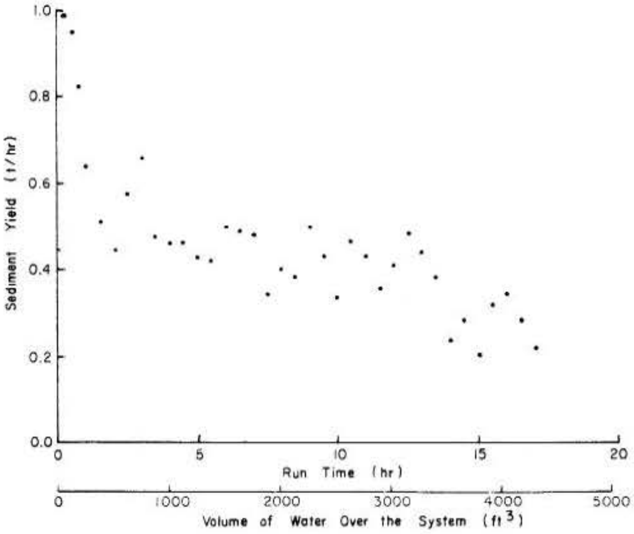

Fig. 6.6. Changes in sediment yield through time for experiment with an initial slope of 3.2 per cent (set 2) on baselevel 4. Time is indexed by volume of water over the system.

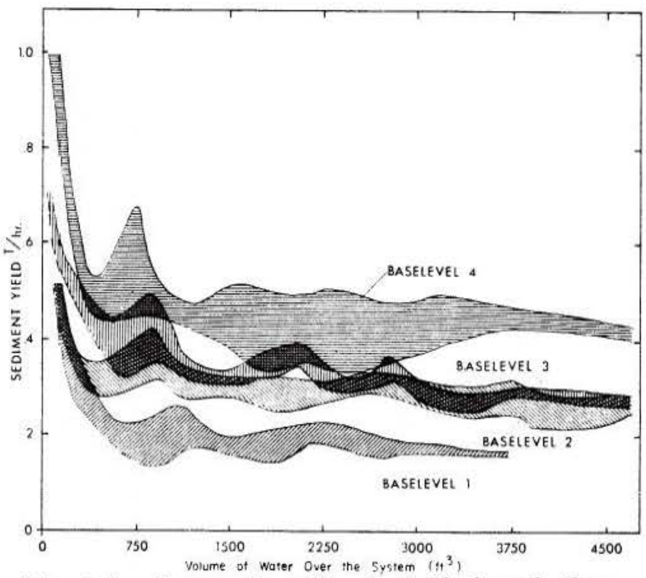

Fig. 6.7. Changes in sediment yield through time for experiment with an initial slope of 3.2 percent on baselevel 5. Time is indexed by volume of water over the system Sequence corresponds to set 2, subset 3.

of the actual rate of sediment yield decrease is needed to predict re-adjustments in the basin.

A better understanding of the mechanics of sediment yield in an altered basin and a satisfactory model to identify these changes in a particular basin is obviously needed.

Sediment Yield Versus Sediment Production

In order to evaluate sediment yield changes from a basin that has been modified by natural or artificial means, it is necessary to establish the relation between sediment yield from the basin and the production of sediment within the basin. Sediment production refers to the production of sediment within the experimental facility by sheet and rill erosion, and by streambed and stream-bank scour. If measured, it would serve as the amount of material moved within the basin, but it is not the same as sediment delivered from the basin.

An attempt has been made to identify the relation between sediment production and the amount of sediment delivered to the basin outlet by developing a sediment delivery ratio. Vanoni (1970, p. 1284) defined sediment delivery as, "A measure of the diminution of eroded sediments, by deposition, as they move from the erosion sources to any designated downstream location. This is usually expressed as a percentage, of ratio, of the on-site eroded material that reaches a given measuring point." In this definition the sediment production, therefore, is the denominator of the ratio and sediment yield is the numerator.

The sediment delivery ratio has been applied in the field (Roehl, 1962; Maner, 1958; Maner et al 1953; Spraberry et al 1960), but sediment production is difficult to evaluate, and these studies have relied on use of Musgrave's (1947) empirical equation to estimate sheet erosion and a sequence of aerial photographs to measure channel erosion. The estimates of sediment production are used with measured values of sediment yield to produce the sediment delivery rate.

Although the concept of sediment production is valid, the actual calculation of this variable is usually qualitative and highly empirical. An important problem with sediment production and sediment yield is the difference in spatial distribution between these two variables. Sediment yield is defined at a point - the point on the watershed at which measurements are obtained (e.g., a gaging station or reservoir). Sediment production occurs at different rates over the total watershed, and it is, therefore, a distributed phenomenon for which it is difficult to obtain reliable data.

In the experimental facility a drop of baselevel produced knickpoints, which migrated up the main channel and its major tributaries, rejuvenating exterior links. As a knickpoint migrated upstream, the drainage area above knick was not influenced by the change in baselevel whereas downstream erosion was accelerated in the channel and along the valley walls in response to the baselevel changes. Knickpoints, therefore, represent the position of the "wave of Dissection" produced in response to the baselevel change. This "wave of dissection" (Howard, 1971, p. 30) identifies the position in the basin at which the baselevel change is causing rejuvenation.

If the movement of the "wave of dissection" could be documented, the resulting increase of sediment production could also be documented. Unfortunately, data on knickpoint migration were difficult to obtain in the experimental facility because knickpoints were easily washed out, and some became small multiple knicks, which frequently coalesced to form one distinct knick at a later time.

Measurement of knickpoint migration in the main channel was attempted. The knickpoint position was measured with time. These measurements were converted into a rate (ft/min) of travel upstream. The results from experiment 2 (baselevel 2) show a decreasing rate of migration with time or distance up the main channel (Fig. 6.8). The least squares equation is:

$$K = 34.48\ V^{-.985} \qquad (6.3)$$

where: K = knickpoint migration in ft/cu. ft. of water over system

V = volume of water over the system (ft^3)

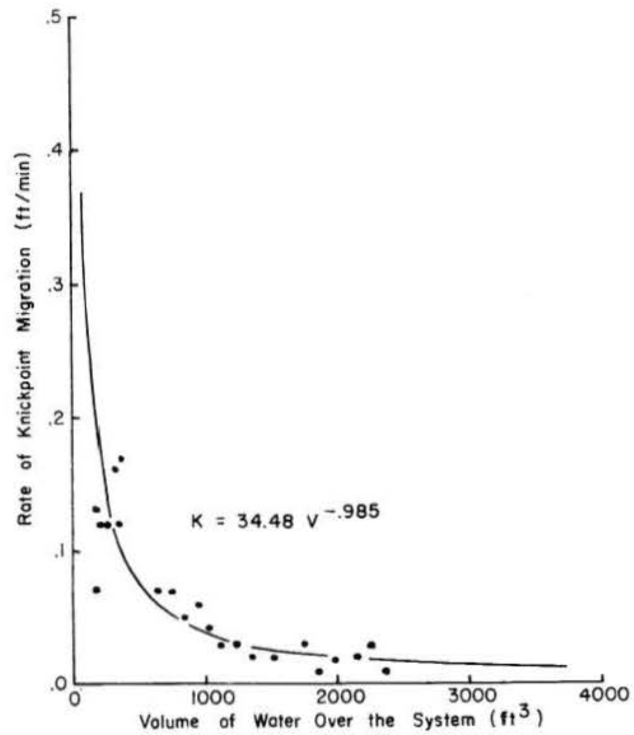

Fig. 6.8. Rate of knickpoint migration through time. Data were obtained at baselevel 2 with an initial slope of 3.2 percent (set 2).

Knickpoint migration was also observed during experiment 1 at baselevel 2. Figure 6.9 records knickpoint movement up the main channel, and knickpoint migration up three tributaries. These data represent only a small portion of the total run time at this baselevel, but the knickpoint was not easily identified later.

Figure 6.9 shows the location of each knickpoint with time. The top curve represents knickpoint migration along the main or central stream in the watershed. The series of lines branching from this main stream line and located below it represents knickpoint migration in three tributaries. The parallel lines indicate a constant rate of knickpoint migration along the tributaries. Knickpoints paused at lower order tributary junctions, although migration along the higher order channel continued, and migration of the knickpoints seemed to occur as though progress up the tributaries was related to the Strahler order.

If rate of knickpoint migration is a function of tributary size, a plot of rates of migration against stream order should produce a direct relation. (fig. 6.10). That is, as order decreases, the rate of knickpoint migration decreases.

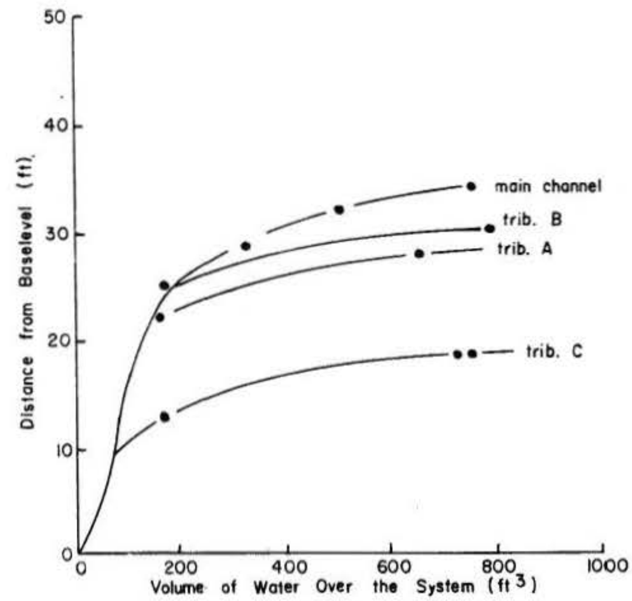

Fig. 6.9. Knickpoint migration shown as distance from the basin outlet after a baselevel change. Time is indexed by volume of water over the system. Network 2, set 1, subset 2 with an initial slope of 0.75 percent was mapped just prior to this change in baselevel.

The migration rate of the knickpoint through time is a negative power function (Eq. 6.3) which follows from the decrease in migration rate with a decrease in Strahler stream order.

Seginer (1966) in a review of gully erosion research found that size of the drainage basin figures prominently in predicting gully advance. He suggested that gully advance could be evaluated from an equation of the form:

$$R = CA^{b} \qquad (6.4)$$

where: R = average annual linear gully advance

A = area of drainage basin
C = constant
b = constant

Seginer's basic equation (Eq. 6.4) is similar to the knickpoint migration equation (Eq. 6.3). If Seginer's assumption is correct that variations in b are attributable to variations in several hydrologic variables, his equation (Eq. 6.4) should provide a good fit to the experimental data. However, when the data from experiment 1, baselevel 2, are plotted the result is an exponential relationship (Fig 6.11).

The independent variables of watershed area, distance from the basin outlet, and Strahler order of stream are all highly intercorrelated and, of course, are clearly related to discharge. As a knickpoint moves further into the watershed, its rate of migration is slowed because of the reduction in basin area and the resulting decline in discharge. Because the precipitation rate is nearly constant over the experimental watershed, a reduction in basin area results in a commensurate reduction in discharge, and this high degree of association is reflected by the high correlation coefficient. In the field differences in geology, soils, topography, and land use will alter the relation between discharge and area to produce a change in the coefficient b or to magnify the variability of the relation between discharge and area.

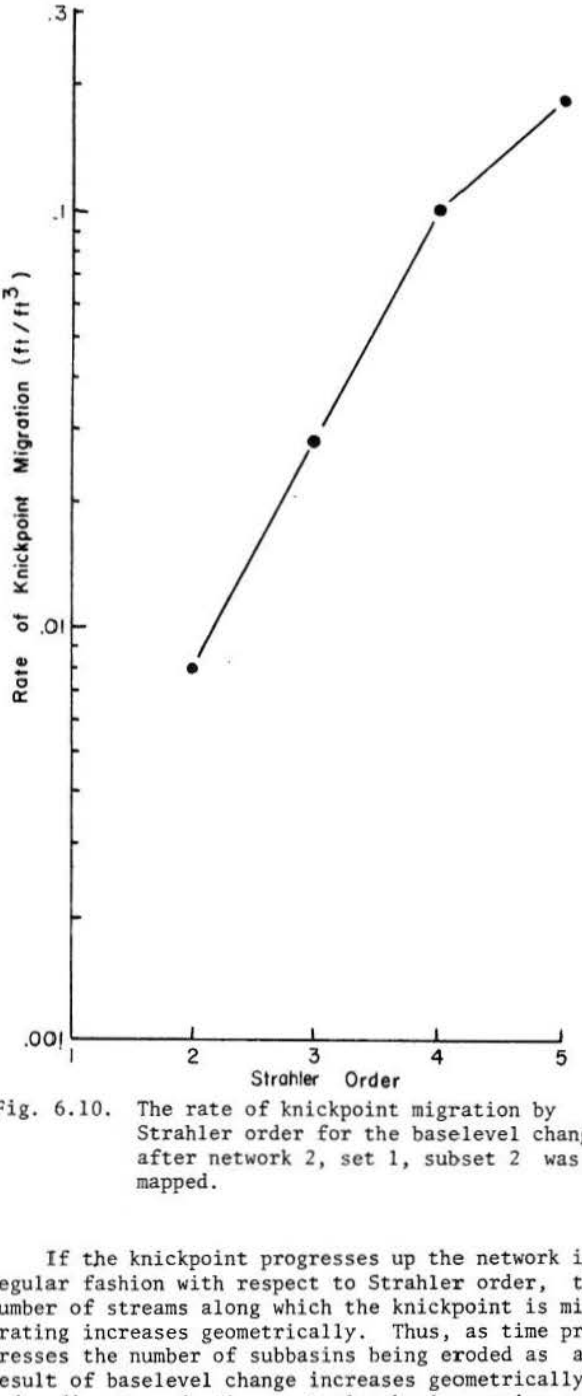

Fig. 6.10. The rate of knickpoint migration by Strahler order for the baselevel change after network 2, set 1, subset 2 was mapped.

If the knickpoint progresses up the network in a regular fashion with respect to Strahler order, the number of streams along which the knickpoint is migrating increases geometrically. Thus, as time progresses the number of subbasins being eroded as a result of baselevel change increases geometrically and sediment production must also be increasing geometrically. However, knickpoints migrate at rates in response to discharge available in the channel. Thus, as the knickpoint migrates farther up the network, the smaller the discharge becomes the slower is knickpoint advance. The effect of this decrease in knickpoint migration is a decrease in the rate of sediment production with time.

Therefore, the knickpoint encounters increased numbers of channels, which increases sediment production, but it also experiences a decrease in water discharge, which in turn decreases sediment production. These two phenomena probably interact to produce a sediment production curve as shown in Figure 6.12. At some time after rejuvenation sediment production reaches a maximum based on the interaction of the two phenomena described.

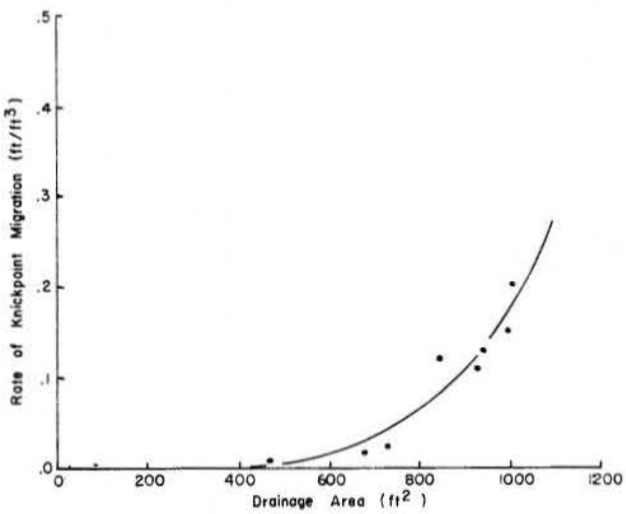

Fig. 6.11. The relation between the rate of knickpoint migration and the approximate drainage area above the knickpoint. Because volume of water is used as an index of time, the rate of knickpoint migration is shown in feet per cubic foot of water.

If, however, a station was recording sediment yield at some distance from the outlet of the experimental basin, the record would be similar to Figures 6.1 and 6.3 showing an exponential decay of sediment yield. For example, Figure 6.12 also shows a plot of sediment yield measured at a hypothetical station four feet from the basin outlet. Initially sediment yields are low as the knickpoint has not migrated past this station. However, as the knickpoint passes the station sediment yields, increase sharply to a maximum but as it progresses upstream, there is an exponential decay to the sediment yield values.

Although both the sediment yield and sediment production curves are shown on Figure 6.12, the relation in time between the two curves cannot be obtained from the present data. It is assumed, however, that at or near the peak of sediment production, the variability noted in the declining limb of the sediment yield graphs (Fig. 6.7) is produced. The difference in sediment produced and the sediment yield measured is a reflection of material stored in the channel upstream from the measuring station. When sediment production is at a maximum, sediment yield has already begun its exponential decay because large amounts of sediment are being stored upstream. This alluvial material may be periodocally flushed past the measuring station, which causes a great variability in sediment yield data.

The relation between sediment production and sediment yield has not been adequately defined with data available. The determination of this relation is important, however, to the understanding of sediment yield changes in a watershed undergoing transition.

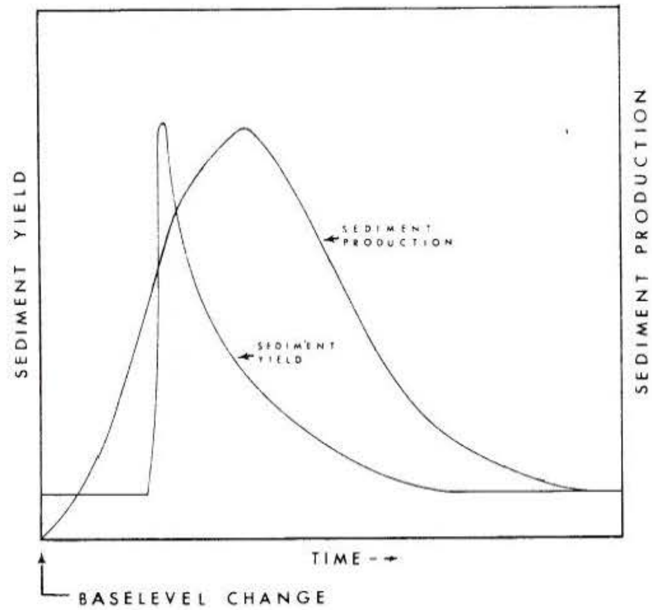

Fig. 6.12. Hypothetical diagram of sediment yield measured at a point and sediment production.

Sediment Storage

Although the relation between sediment yield and sediment production may result in increased variability of sediment yield values, the interaction between the two variables also suggests severe impact on the main channel. If sediment production increases geometrically, the main channel downstream must cope with increasing sediment loads routed from the eroding channel system. These increased sediment loads cause the main channel to widen and braid, and to deposit some of this excess sediment. Thus, initial degradation, produced by a baselevel change in the experiment, causes aggradation in the main channel, as erosion progresses up the network.

Schumm (1961), studying emphemeral channels with actively eroding and aggrading reaches, suggested a similar conclusion that aggrading reaches were apparently a result of high sediment yields in the headwater parts of the drainage basin. The main channel cannot transport this increased load, and the result is localized aggradation.

Although it is not possible to measure the interaction of sediment production and sediment yield in the experimental basin, it was possible to document changes in the main stream profile that presumably reflect changes of sediment delivery to the main channel. A sequence of profiles measured at baselevel 4 (Table 6.1) show these changes (Fig. 6.13). Only the first 20 ft. of the profiles are shown. The first profile was obtained after 2 hours of run on this baselevel (504 ft^3 of water). The second profile was recorded after 2 more hours of run (1008 ft^3 of water) and shows continued degradation of the channel. The third profile in Figure 6.13 was surveyed after an additional 2 hours of run (1512 ft^3 of water); it shows continued degradation above 13 ft. from the outlet. However, there is an increase in the elevation along the first 13 ft. of this profile which represents deposition of alluvium near the mouth of the basin. Deposition in the first 10 to 20 feet of the profile was evident following baselevel lowering in both experiments.

The boundary between the "bedrock" or uneroded material and the alluvial fill was easily distinguished in an excavation. Figure 6.14 shows alluvial fill, which reaches a depth of 0.3 ft. in some places, over a 4 ft. width of valley. Unfortunately, sediment derived from upstream cannot be distinguished from material derived from the surrounding slopes or from lateral migration of the channel. Certainly, the increased depth of alluvial fill near the valley side is due to colluvium. Also, the maximum depth of fill is due to an older channel which has shifted. The lateral migration of the channel caused extensive bank caving which contributed to the depth of the alluvial fill. Nevertheless, the main channel profile and the cross section show the aggradation of the main channel.

The period of aggradation was sometimes followed by channel narrowing and erosion into the alluvial fill. As sediment production upstream decreases, the decreased sediment load in the main channel allows incision.

The observation of these changes in the main channel, changes in the long profile, and changes in the main channel cross section coupled with the regularity of knickpoint migration and the variability in sediment yield with time, led to the formulation of an hypothesis of complex response of drainage basins to channel incision (Schumm and Parker, 1973, Schumm, 1977.) In this hypothesis, an initial degradation in response to baselevel change is followed by a period of deposition that results from increased sediment production upstream. As sediment production declines, the main channel narrows and incises into the previously deposited alluvial fill.

Summary

The overall trend of sediment yield with time, as a result of rejuvenation of the basin, can be described as an exponential decay. Initial differences in sediment yield between the two experiments are related to differences in initial conditions that also influence mode of growth. With a drop in baselevel, sediment yields are initially higher but then decline to a value which is indicative of little channel growth.

With no initial drop in baselevel, sediment yields do not obtain the high values of experiment one. This results from incision of the skeletal network directly into the watershed surface and the transport of sediment farther to the outlet, during the initial period of development. Higher sediment yield rates are maintained in time, however, as the network continues to grow internally, which is a characteristic of Hortonian growth. With the passage of time the channel system also becomes a more efficient conveyor of sediment, which also helps to maintain the higher sediment yield values.

Sediment yields were highly variable in time. In natural basins changes in climate and land use also influence the variability of sediment yield. Thus, imposed on this long term sediment yield curve with its associated variance would be short term changes. This makes the determination of the effect of short term sediment yield changes very difficult to predict. In essence, one would be confronted with two distributions (the long and short term) each with its own variance component. During short periods of sampling these variances are additive, which could result in a higher variance than either distribution alone.

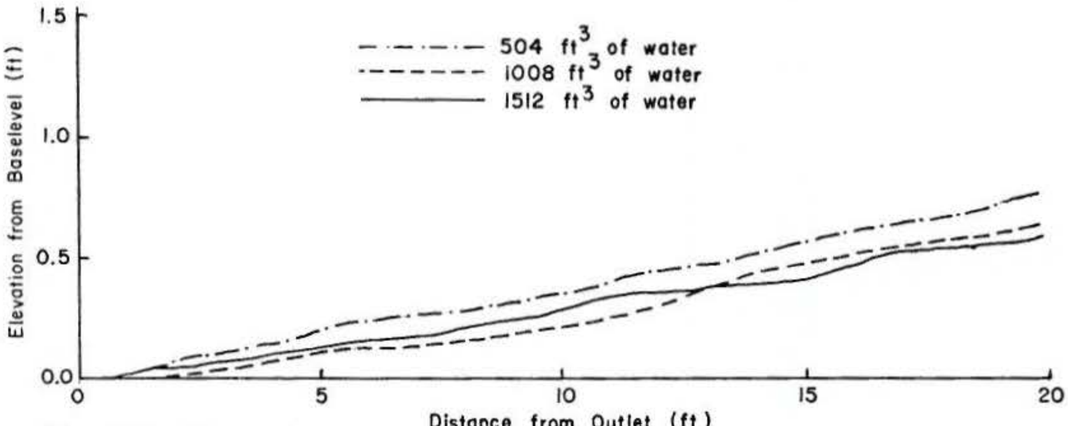

Fig. 6.13. Changes in the profile of the main channel after baselevel 4 during the first experiment on an initial slope of 0.75 percent (set 1). Figure shows the first 20 feet of the profile from the basin outlet.

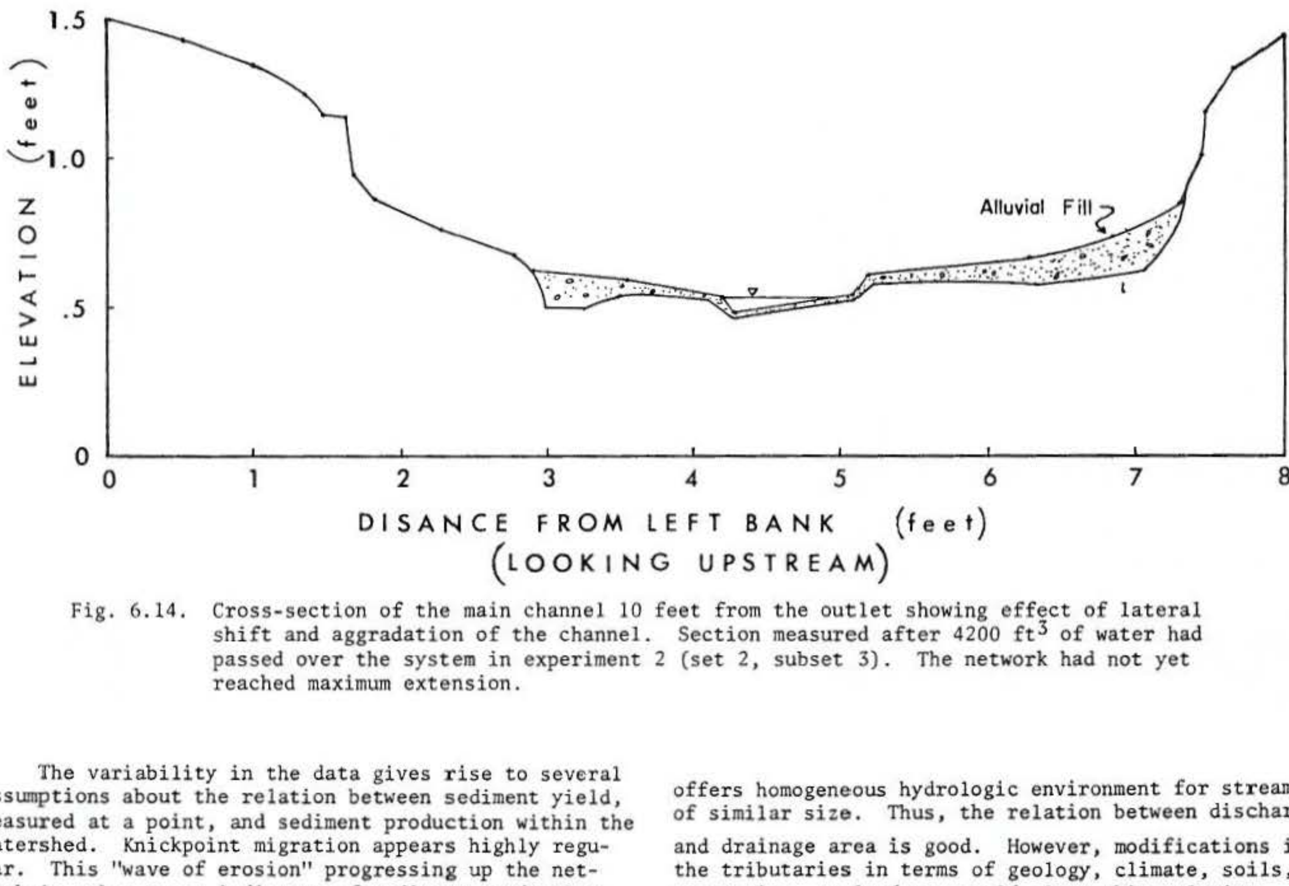

Fig. 6.14. Cross-section of the main channel 10 feet from the outlet showing effect of lateral shift and aggradation of the channel. Section measured after 4200 ft^3 of water had passed over the system in experiment 2 (set 2, subset 3). The network had not yet reached maximum extension.

The variability in the data gives rise to several assumptions about the relation between sediment yield, measured at a point, and sediment production within the watershed. Knickpoint migration appears highly regular. This "wave of erosion" progressing up the network is taken as an indicator of sediment production. That is, sediment production at a particular baselevel reaches some maximum, and then it declines with time (Fig. 6.12). The time of maximum sediment production is when there is maximum interaction between the two factors of rejuvenation of increasing number of streams in the network, which increases sediment production, and the decreasing drainage area available for each channel upstream, which decreases sediment production.

Knickpoint migration appears related to Seginer's non-linear equation of growth rate against drainage area above the knick (Eq. 6.4). The experimental basin offers homogeneous hydrologic environment for streams of similar size. Thus, the relation between discharge and drainage area is good. However, modifications in the tributaries in terms of geology, climate, soils, vegetation, or land use would alter this relation.

The increases in sediment production upstream affected the main channel near the basin outlet. The main channel was observed to widen, braid, and deposit alluvial material. This is indicated by the change in the main channel profile and in the alluvial fill found in the main channel cross section. Such a situation has been observed in the field in ephemeral streams that are actively degrading. As time progressed and upstream sediment production declined, the channel narrowed and incised into its own alluvial fill. This sequence was generalized in an hypothesis termed the complex response of channel incision.

CHAPTER VII

HYDROLOGIC RESPONSE

Determining hydrologic characteristics of a drainage basin is an important activity in the hydraulic design of most structures. Frequently estimates must be made for ungaged watersheds. Because this problem is confronted so often, many techniques for estimating hydrographs for ungaged basins have been developed. One of the most used techniques is that of the unit hydrograph. Proposed by Sherman (1932), the unit hydrograph concept requires the assumption of linearity (superposition). The unit hydrograph is defined as the direct runoff resulting from one inch of effective rainfall falling uniformly over the basin at a constant rate and specified duration.

One technique attempts to describe a unit hydrograph indirectly through the use of geomorphic parameters. This synthetic unit hydrograph was first developed by Synder (1938). Later attempts at expanding the procedure were initiated by Commons (1942), Langbein et al. (1947), Taylor and Schwarz (1952), Gray (1961, a, b,), and Gray (1962). A comparison of the different techniques was given by Hanson and Johnson (1964).

Multiple regression has also been used to identify relations between the hydrologic output of a basin and the controlling geomorphic factors within the basin. Wong (1963), Nash and Shaw (1966), Rodda (1969), And Thomas and Benson (1970) have used multivariate relationships to predict some hydrologic parameters.

One of the basic problems with studies of this type is the highly interrelated nature of many geomorphic variables. Many geomorphic variables now in use have not been identified as to their dependence with other variables. For example, there appears a good correlation between relief and drainage density, but whether both are dependent variables with respect to geology has been answered only partially (Hadley and Schumm, 1961). Hydrologic studies usually use basin descriptors that are easily obtained without regard to the interdependence of the variables used.

It is necessary to define the unit hydrograph from known rainfall events (input) and the hydrograph response or output. The problem of knowing the input and output and attempting to derive a function to describe the hydrologic character of the drainage basin is known as system identification. It is much more difficult than deriving output from input when the system is known, which is system prediction (Dooge, 1973).

Using an experimental facility, in which geomorphic variables can be controlled, provides an opportunity to observe the hydrologic response to different watershed configurations. Therefore, a major objective of this research was to determine the effects of selected geomorphic characteristics on basin response.

Experimental Procedure

Two sets of hydrographs were obtained during the experimental study. The first set was obtained from networks 1, 3, 4, and 5, set 1, subset 2, when the watershed was increasing in drainage density and in relief as baselevel was lowered (Table 2.4). The second set was obtained from networks 1, 2, 3, and 4, set 2, subset 3 with a constant baselevel as the drainage system went to maximum extension and then abstracted (Table 2.4). Network 2 represented maximum extension of that drainage system.

No hydrographs were produced during the early part of the experiment (e.g., set 1, subset 1 or set 2, subset 1) when rapid changes in the geomorphology were taking place and when large amounts of sediment were delivered to the basin mouth, which made hydrograph measurements difficult. Thus, hydrographs are not available when the geomorphology was undergoing its greatest change.

The procedure was the same during generation of both sets of hydrographs. An equilibrium hydrograph of 8 to 16 minute input duration was followed by a series of partial equilibrium hydrographs of one minute input duration (Fig. 2.4). The partial equilibrium hydrographs were repeated from 3 to 10 times. The procedure was also used to help negate the influence of infiltration on the hydrograph, however, this was not altogether successful. However, the replications were sufficiently consistent to allow the use of one representative hydrograph from each series in the subsequent analysis.

Three intensities of precipitation were available for the generation of hydrographs for the first set of hydrographs. The highest intensity was 2.61 in/hr. The medium intensity was 2.05 in/hr., and the lowest intensity was 1.29 in/hr. A fourth and smaller intensity was available but the influence of wind was so great that it was not used.

The wind proved very troublesome during this portion of the experiment. Even light breezes of 5 mph could severely alter a hydrograph, and they caused variability in hydrograph replication. This wind problem was eliminated during the second experiment (set 2, subset 3) by construction of a building over the REF, which greatly reduced the variability among hydrographs, and permitted the use of the smallest precipitation intensity.

The sequence of hydrograph generation was always from higher intensity to lower. Thus, the channel forming discharge (the highest intensity) was used first. This procedure may have affected hydrograph characteristics, because channel morphology characteristics (e.g., roughness and width) may not have been characteristic of the lower intensity flow.

Confinement of the REF in a building resulted in the loss of three sprinklers as well as the development of a new configuration of sprinklers for each intensity. Because of the loss of sprinklers, the intensities for data set 2 are lower. The four intensities available were 2.42 in/hr (the channel forming discharge), 1.83 in/hr, 1.21 in/hr, and 0.83 in/hr. This represents a 7 percent reduction of maximum intensity. The procedure of hydrograph generation was as before.

Representative Hydrographs

The replication of the one minute duration hydrographs allowed testing of the repeatability of hydrograph generation. Qualitatively the replications are excellent with little variability among hydrographs (Fig. 7.1).

Perhaps one of the best quantitative measures of repeatability is the variation in volume of the hydrographs in a sequence. Table 7.1 shows the mean percent difference between the input and output volumes measured in cubic feet. Input volumes were calculated from the input intensities already given. Of importance here is the standard deviation of this statistic as a measure of the spatial variability of the rainfall. The variability does not appear large. The second set of data (hydrographs from set 2, subset 3, Table 7.1) shows even less variability, which is attributed to the lack of wind effects.

The mean percent difference between input and output is high (Table 7.1). This difference incorporates experimental error, and water losses due to initial abstractions such as evaporation and infiltration. In order to estimate the percentage experimental error, a plastic sheet was spread over the surface of the last network (set 2, subset 3, network 4). This eliminated infiltration and the major portion of initial abstractions. The mean percent difference between input and output volumes for this test was about 4 percent (Table 7.2), which must be attributed to experimental error. For example, the minus value in the lowest intensity indicates that the output volume was slightly greater than the input volume, which is not possible. The 1.21 in/hr intensity had a mean and standard deviation that is indicative of of what one would expect. That is, there is a difference near zero and a standard deviation that reflects replications with both positive and negative values, which identified experimental error around zero.

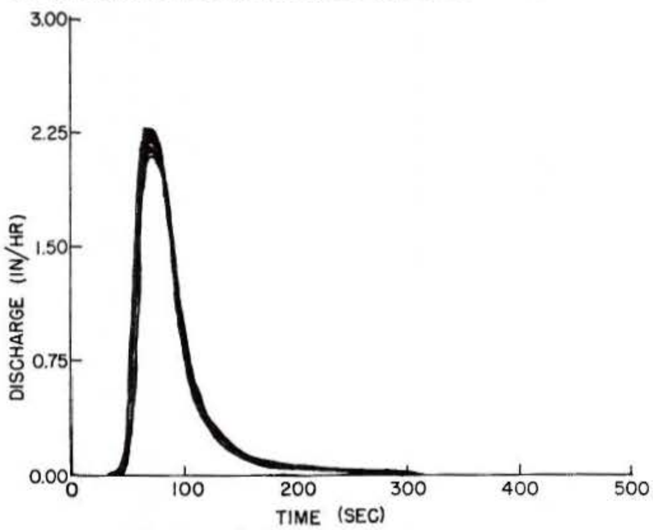

Fig. 7.1. Series of discharge hydrographs showing repeatability. Precipitation input of 2.42 in/hr for one minute duration. Hydrographs generated on network 1, set 2, subset 3.

Because the hydrograph replications appear similar, one hydrograph from each series was picked as representative. This procedure reduced the number of hydrographs used in the analysis from approximately 160 to 32.

Table 7.1. Volumes of Water Obtained from Hydrographs Generated in Each Experiment

Hydrographs obtained from networks 1, 3, 4, and 5; set 1, subset 2

Net-Work	Rain-fall Inten-sity (in/hr)	No. of Hydro-graphs	% Difference between Input and Output Volumes: Mean	Stan. Dev.
1	2.61	2	27.3	8.2
1	2.05	2	32.4	6.4
1	1.29	2	47.6	10.3
3	2.61	7	29.5	5.6
3	2.05	4	41.2	3.2
3	1.29	6	57.1	7.2
4	2.61	9	34.1	9.4
4	2.05	7	29.4	7.2
4	1.29	9	42.9	12.4
5	2.61	6	29.5	8.7
5	2.05	4	32.4	11.5
5	1.29	4	33.3	6.3

Hydrographs obtained from networks 1, 2, 3, and 4; set 2, subset 3

Net-Work	Rain-fall Inten-sity (in/hr)	No. of Hydro-graphs	% Difference between Input and Output Volumes: Mean	Stan. Dev.
1	2.42	3	31.6	3.6
1	1.83	3	40.3	1.2
1	1.21	3	53.7	0.3
1	0.83	7	69.1	1.5
2	2.42	3	44.5	1.3
2	1.83	3	47.1	9.0
2	1.21	4	61.1	1.4
2	0.83	3	70.1	0.6
3	2.42	3	39.2	0.4
3	1.83	7	42.9	1.7
3	1.21	3	51.5	0.9
3	0.83	4	61.3	1.6
4	2.42	4	30.7	3.0
4	1.83	4	46.5	5.8
4	1.21	5	41.2	2.9
4	0.83	3	59.7	1.3

Table 7.2. Experimental Error Calculated from Input and Output Volumes of Water Using Hydrographs from Network 4, Set 2, Subset 3. System Covered with Plastic to Eliminate Infiltration

Rainfall Intensity (in/hr)	No. of Hydrographs	% Difference between Input and Output Volumes	
		Mean	Stan. Dev.
2.42	3	5.3	3.8
1.83	3	7.2	2.1
1.21	3	2.1	4.0
0.83	3	-2.4	8.6

The Effects of Increasing Relief and Drainage Density on Hydrograph Peaks

This section is concerned with the hydrographs generated on networks 1, 3, 4, and 5 in set 1, subset 2. These networks showed an increasing drainage density through time and each network was subject to a change in baselevel. Thus, each network had an overall increase in relief due to the lowering of baselevel and a corresponding increase in drainage density.

Frequently relief has been used as an important variable in expressing hydrograph characteristics (Hickok et al, 1959); Nash, 1966). These attempts have primarily been directed at determining the timing characteristics of the basin or lag time. Lag time is defined as the time difference between the centroid of a storm event and the resulting peak discharge. Because the water velocity is directly proportional to slope, the relations derived have shown that as relief increases the delay in peak runoff decreases.

Hickok et al. (1959) suggested that drainage density also had an inverse relation with lag time. Considering drainage density alone, this relation appears reasonable, as the more channels that are available (the higher the drainage density) the more efficient the system should be at evacuating water from the basin.

Thus, both hydraulic considerations and empirical evidence obtained in the field suggest that timing is decreased as relief and drainage density are increased. That is, efficiency of water movement from the basin is increased as both relief and drainage density are increased. It seems reasonable, therefore, that the peak discharge for a given input of rainfall will also increase as these geomorphic parameters increase.

As both drainage density and relief increase through the first experiment (set 1, subset 2), the combined effects of these two variables should produce a more efficient hydrologic system, which should result in higher peak discharges as the stream network evolves.

The representative hydrographs are used in this analysis. As shown in Table 7.3, there is little variation in the hydrograph peaks for a sequence of hydrographs generated. Thus, little is gained by including all the hydrographs of a series.

To test changes in the representative hydrographs with changes in both relief and drainage density, a ratio between the hydrograph peak in inches per hour from the one minute duration input (Q_p) and the equilibrium discharge rate in inches per hour taken as the maximum rate from the equilibrium hydrograph (Q_e) was calculated. This dimensionless ratio, which ranges between zero and one for each intensity, is used in order to compare relative peak discharges among the rainfall intensities available.

Table 7.3. Variability of Peak Discharge among Implications for One Minute Input Duration Hydrographs

Hydrographs from networks 1, 3, 4, and 5; set 1, subset 2				
Net-Work	Inten-sity (in/hr)	No. of Hydro-graphs	Q_p of Repre-sentative Hydro. (in/hr)	Stan. Dev. of Q_p of All Hydro-graphs
1	2.61	2	1.54	-
1	2.05	2	1.13	-
1	1.29	2	0.57	-
3	2.61	7	2.29	.010
3	2.05	4	1.48	.001
3	1.29	6	0.75	.004
4	2.61	9	2.41	.009
4	2.05	7	1.70	.003
4	1.29	9	0.86	.002
5	2.61	6	2.59	.008
5	2.05	4	1.80	.004
5	1.29	4	0.88	.002

The geomorphic variable used as the independent variable is the ruggedness number (R_g) (Strahler, 1958) which combines both relief and drainage density in one dimensionless value (relief times drainage density).

As the ruggedness number increases (Fig. 7.2), the Q_p/Q_e ratio approaches a maximum. Each intensity shows nearly the same percentage increase over the range of ruggedness numbers plotted. For example, the highest intensity has a 40 percent increase in the Q_p/Q_e ratio between the lowest and highest ruggedness number. The mid-intensity has a 37 percent increase and the lowest intensity has a 35 percent increase.

A hypothesis for the downward shift in the Q_p/Q_e ratio at the lower rainfall intensities is that different runoff magnitudes are affected differently by the geomorphic configuration of the basin. Changes in the overall basin parameters of relief and drainage density reflect changes in slope angles between divides and the channel, length of overland flow, channel geometry, amount of alluvial fill in the channel, and other such internal changes that have a greater impact on small quantities of water generated by the lower rainfall intensities. That is, the outputs from the higher intensities are less dependent on watershed geomorphology but further data are needed to explore this hypothesis.

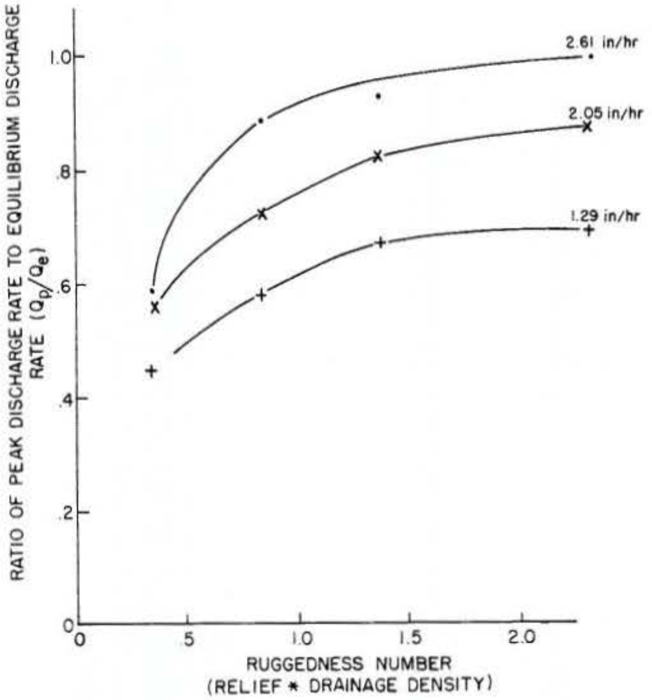

Fig. 7.2. Changes in the ratio of peak discharge rate to equilibrium discharge rate (Q_p/Q_e) for changes in the ruggedness number. Each precipitation intensity is shown (set 1, subset 2 data.

An increase in ruggedness number produces a dramatic increase in the Q_p/Q_e ratio between the R_g values of 0.348 and 0.856 (Fig. 7.2). Further increases in the ruggedness number do not produce a correspondingly large increase in the Q_p/Q_e ratio. This occurs for all input rates and results in the curvilinear response shown. Thus, the hydrographs produced appear to maintain a nearly constant Q_p/Q_e ratio, as the ruggedness ratio continues to increase.

One of the factors which affects the large changes observed in the Q_p/Q_e ratio for changes in lower ruggedness numbers is the change in the amount of overland flow. Although the ruggedness number and the area of interfluves involved producing overland flow are related, the position of interchannel area is not indexed by the ruggedness number. The channel system had fully developed only the lower two-thirds of the basin, when the first hydrograph set was generated (Appendix A, set 1, subset 2, network 1). Thus, nearly one third of the basin was characterized by overland flow. This upper one-third of the basin was dissected during later evolution to produce the higher ruggedness numbers. After the upper area was dissected, further channel growth produced little changes in the peak rates of the hydrographs.

The ruggedness numbers (from 0.348 to 2.314) do not span the range of values reported in natural basins. Strahler (1958, p. 296) reports values of 0.022 for the ruggedness number on the Gulf Plain of Louisiana, 0.35 for the Ozark Plateau of Illinois, 1.00 for the Berdugo Hills in California, and 1.10 for the Perth Amboy Badlands of New Jersey. In rapidly eroding areas such as bedlands, the ruggedness number is greater than one but the range of values in nature has not been adequately defined. Nevertheless, the range of the ruggedness number is large and shows that hydrologic response does depend on the relief and drainage density.

Sediment Yield

Sediment samples were collected during the generation of a one-minute duration input hydrographs and a series of sediment hydrographs were prepared for networks 3, 4, and 5 (set 1, subset 2). Approximately five samples of total sediment yield were collected during a hydrograph run in an attempt to define sediment discharge. Considering the variability of sediment yield from the basin, these few samples probably cannot adequately describe the sediment outflow. However, this procedure is similar to the techniques used to obtain such data in the field and, can, within the limits of variability, be used to describe the relations between sediment yield and the hydrologic and geomorphic characteristics of the basin.

The sediment yield and the associated representative hydrographs are shown in Appendix B. These sediment yield graphs, although not completely defined because of the small number of samples, show a consistent sediment yield peak that precedes or coincides with the hydrograph peak. This is called a leading sediment discharge (Guy, 1970, p. 22). Colby (1963) stated that such a timing characterization was the result of a short distance of travel from the point of erosion to the stream channels, which contain little flow prior to the storm runoff. These two conditions are characteristic of the experiment. High drainage density values reflect the short distances between interfluve and channel, and the experimental procedure of hydrograph generation resulted in no flow in the channel prior to the one minute rainfall duration.

As ruggedness number increases, the peak sediment yield for a one minute duration storm increases (Fig. 7.3).

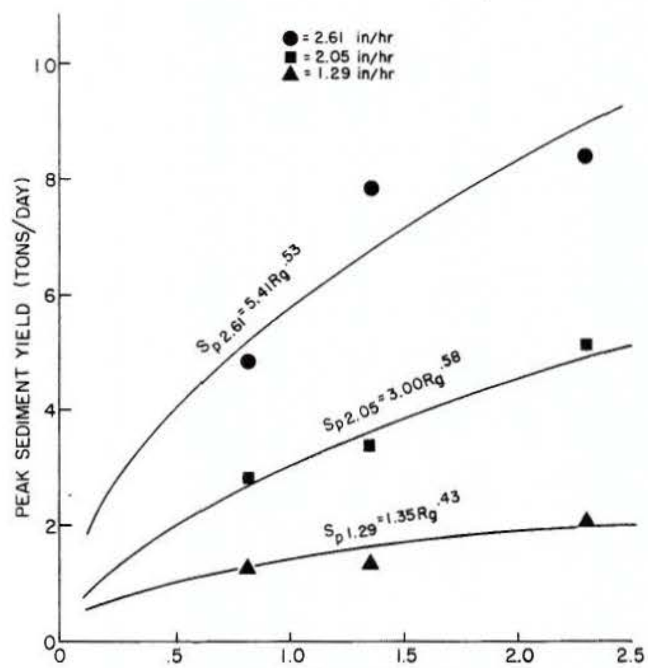

Fig. 7.3. Changes in the peak sediment yield (S_p) at a given intensity from one minute duration input hydrographs with changes in ruggedness number. (R_g) Each precipitation intensity is shown (set 1, subset 2 data).

A nonlinear equation is used to fit the date because it is assumed that at a ruggedness number of zero the sediment yield would be zero for all intensities. Also, it appears that the rate of increase of sediment yield declines at the higher ruggedness numbers. It is difficult to identify the curve accurately with only three data points, but the flattening of the curve at higher ruggedness values appears reasonable for two reasons. First, the peak discharge for the highest rainfall intensity becomes the equilibrium rate (the rainfall input rate) as the relief and drainage density increase and, thus, more discharge is simply not available for carrying away sediment. Second, as ruggedness number increases in response to an increase in both drainage density and relief, there will be an upper limit to the sediment yield from the basin. That is, it is conjectured that sediment yield could not increase infinitely as the basin became steeper, but it must finally reach and maintain a maximum value. The identification of such a maximum must await data at larger values of the ruggedness number.

For a given ruggedness number, sediment yield appears to increase at an increasing rate with increases in precipitation intensity and, therefore, discharge. For example, at a ruggedness number of 0.8, the precipitation rate is increased by 51 percent between the lowest and highest rainfall intensity applied while the peak sediment discharge increases by 76 percent.

The relation between peak sediment yield and the ratio Q_p/Q_e is shown in Figure 7.4. Because of the direct causal relation between discharge and sediment yield, the non-linear equation:

$$\log S_p = -1.143 + 2.082 \frac{Q_p}{Q_e} \tag{7.1}$$

where: S_p = peak sediment yield

Q_p/Q_e = the ratio of peak discharge to equilibrium discharge

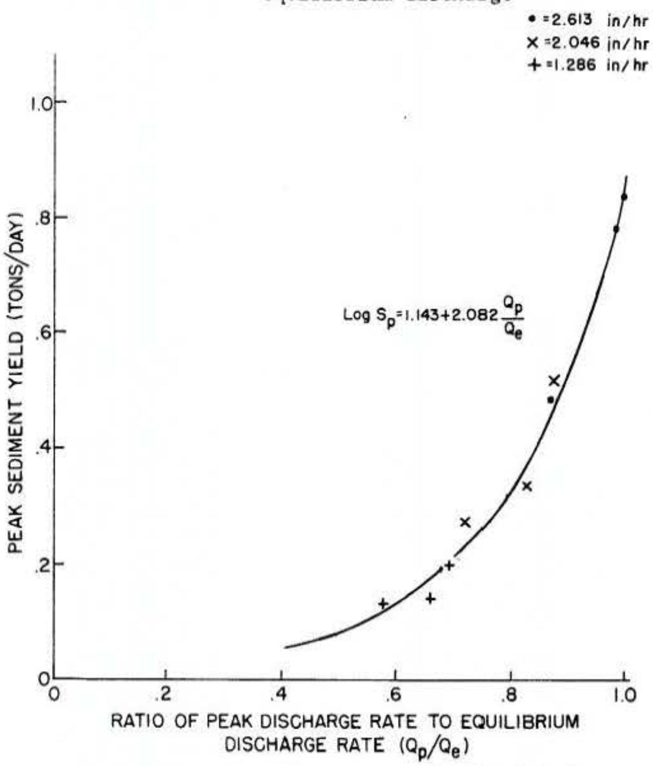

Fig. 7.4. Changes in peak sediment yield with changes in the ratio of peak discharge rate to equilibrium discharge rate. All three discharges are shown for set 1, subset 2 data.

fits the data well. Indeed, all data points from all three networks are shown in Figure 7.4. The ruggedness number varies among these data points by as much as 63 percent. The use of the Q_p/Q_e ratio combines the effect of rainfall intensity and the geomorphic parameter, the ruggedness number, as shown on Figure 7.2. Indeed, the ratio Q_p/Q_e incorporates the effects of the basin geomorphology as well as such properties as infiltration characteristics and channel geometry. There is, however, a direct relation between the integrated effects of the Q_p/Q_e ratio and sediment yield. An increase in precipitation intensity or an increase in the ruggedness number or both results in an increase in peak sediment yields.

At low rainfall intensities and low ruggedness numbers, the increase in peak sediment yield for an increase in rainfall or ruggedness number is small (Fig. 7.4), although more data are needed at these lower values to better define the curve. The overall shape of the curve suggests that some point exists where an increase in the independent variable begins to produce a significant increase in sediment yield. With the data available this point is suggested by the form of the equation but cannot be defined.

As the independent variable (Q_p/Q_e) approaches the value one, its limit, the peak sediment yield goes to 8.3 t/day. This sediment yield value presumably is the maximum possible in the basin. If, however, the ruggedness number or rainfall intensity were increased the maximum value of the peak sediment yield should also increase. However, continued increases in peak sediment yield is not justified; there must be some upper limit to the peak rates of sediment that can be derived from a basin.

Effects of Geomorphology on Hydrograph Timing

Sherman (1932) introduced the unit hydrograph procedure, which in various forms is used as a primary method of hydrograph analysis. This method of analysis is based on three assumptions (Johnson and Cross, 1949):

1. For a given drainage basin, the duration of surface runoff is essentially constant for all uniform-intensity storms of the same duration, regardless of differences in the total volume of the surface runoff.

2. For a given drainage basin if two uniform-intensity storms of the same length produce different total volumes of surface runoff, then the rates of surface runoff at corresponding times t, after the beginning of two storms are in the same proportion to each other as the total volumes of the surface runoff.

3. The time distribution of surface runoff from a given storm period is independent of concurrent runoff from antecedent storm periods.

In systems terminology these three criteria can be summarized by stating that the relation between rainfall excess and surface runoff is a linear time-invariant system.

That the system is neither linear nor time-invariant is well known (Dooge, 1973, p. 85), but the unit hydrograph procedure is simple, and its predictive powers have been suitable for a variety of engineering applications. As the mechanics of hydrologic processes becomes better known and non-linear procedures are identified and simplified, the use of non-linear techniques have become more widespread.

This paradigm of first using linear techniques and then developing greater sophistication and complexity toward non-linear techniques is a common cycle in science. Thus, it can be expected that further growth in the non-linear techniques will occur.

It is important to determine whether a linear system adequately describes the basin under consideration and to what degree changes in the geomorphology of the basin produce severe non-linear components. By examining changes in linearity with changes in basin configuration some insight into the geomorphic components that produce non-linearity can be obtained.

To produce dimensionless hydrographs for comparison of the hydrology among basins, the instantaneous unit hydrograph (IUH) is used. The instantaneous unit hydrograph is derived by reducing the duration of excess rainfall to zero time.

Several methods of deriving the IUH have been proposed. This study utilizes the method proposed by Nash (1957), which is a cascade of linear reservoirs. Using the method of moments on the input and output of a hydrologic system, a best fit to the hydrograph is obtained by deriving a number of reservoirs (n), which need not be an integer, and the storage delay time in each reservoir (K). Thus, the appropriate delay for a basin outflow can be obtained by routing an input through the cascade of n reservoirs.

Utilizing the 2 parameter gamma distribution, Nash derived the equation of the unit hydrograph with K being the scale factor and n being the shape factor. The resulting equation for the IUH, known in hydrology as the "Nash model," is:

$$h_o(t) = \frac{(t/K^{n-1} \exp -(t/K)}{K \, 7(n)} \qquad (7.2)$$

where: $h_o(t)$ = ordinate of IUH
n = number of reservoirs
K = storage delay time of each reservoir

Characteristics of Lag Time

One of the important characteristics of hydrologic response is the lag time (t_L). Variously defined, it represents the effect of geomorphology on storage and delay of the hydrograph output. Dooge (1973) takes note of the fact that if a system is assumed linear, as it must when using the unit hydrograph technique, the lag time is independent of the intensity and duration of precipitation excess. This provides a means of examining the linearity of basin response because departures from independence of rainfall intensity reflect non-linearity.

If lag time is not independent of intensity and duration of rainfall excess it should reflect the geomorphic conditions which impose this condition. Differences in infiltration can be ruled out as a causal factor because it has already been shown that infiltration can be assumed equal through all the runs.

Nash defined lag time as the time difference between the centroids of rainfall excess and runoff outflow. Evaluating Nash's model by the method of moments, the first moment (M_1) is equal to the number of reservoirs (n) times the reservoir storage, (K) and the first moment (nK) represents the lag time of the centroid of the IUH (Chow, 1964, p. 14-29). Thus, if the lag time is plotted against the independent variable rainfall intensity, the resulting relation should yield a slope value of zero if the assumption of linearity is valid. The greater the slope of the resulting relation the greater is the violation of the assumption of linearity.

Using hydrologic data from set 2, subset 3, the plot of lag time versus rainfall intensity is shown in Figure 7.5. This data set consists of four networks at the same base-level, and, therefore, the same overall relief, but with changes in drainage density. Drainage density increased to network 2, and then abstraction began with networks 3 and 4 showing a progressive decline in drainage density.

The hydrograph series generated on the plastic surface which resulted in the further loss of channels is also shown on Fig. 7.5. Length of channel was identified by examining the channel pattern, as water flowed over the plastic, and it was estimated to be the same channel pattern as network 4 with a first and second Strahler order channels removed. Thus, a drainage density value of 0.099 ft/ft^2 was inferred.

Figure 7.5 shows that, as density decreases, the slope of the least squares equation increases. Thus, as the drainage density decreases, the departure from a linear system increases. The least squares equations between lag time and rainfall intensity are summarized in Table 7.8. The equations (Table 7.8) are good as the r^2 values show.

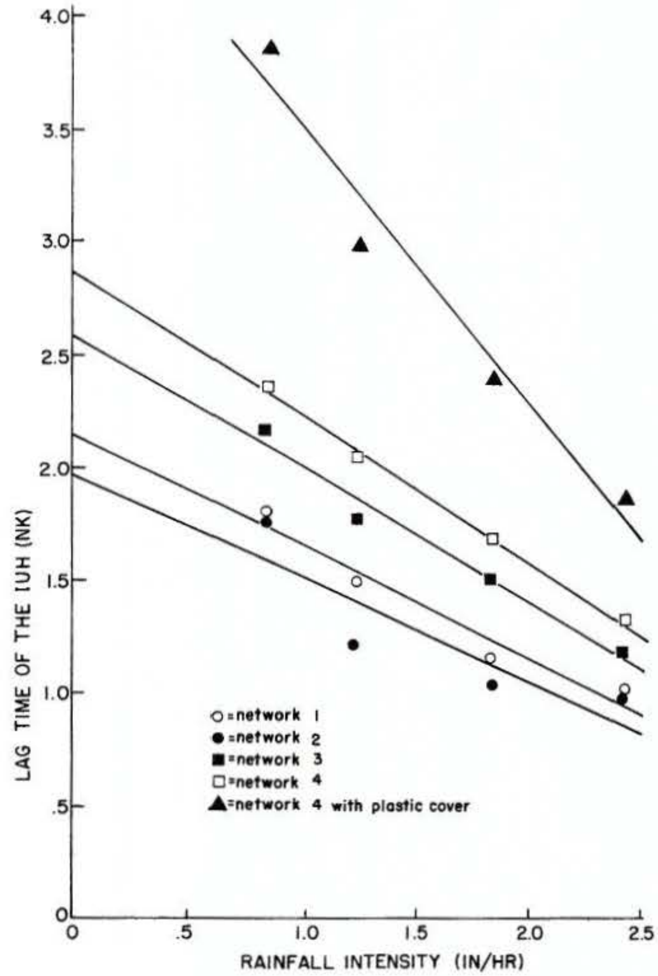

Fig. 7.5. Changes in the lag time of the instantaneous unit hydrograph (IUH) for each available precipitation intensity. Relation is shown for each network in set 2, subset 3.

A notable exception appears to be the data from network 2, which represent a basin at maximum extension.

Table 7.7. Summary of Regression Equations for Relation between IUH Lag Time (t_L) and Rainfall Intensity (I) for Each of the Networks in Set 2, Subset 3

Network	Drainage Density (ft/ft^2)	Regression Equation	r^2
1	0.48	$t_L = 2.5 - 0.498\ I$	0.96
2	0.50	$t_L = 1.97 - 0.457\ I$	0.76
3	0.46	$t_L = 2.50 - 0.594\ I$	0.97
4	0.37	$t_L = 2.87 - 0.646\ I$	0.99
4*	0.099**	$t_L = 4.68 - 1.201\ I$	0.95

*Network 4 covered with plastic.
**Drainage density inferred.

Here the problem appears to be the fitting of a linear relation to data that show a definite non-linear trend.

As stated previously the slope of the equations in Table 7.4 should have a value of zero for a linear system. Thus, we can use these slope values as a function of non-linearity and plot them against the geomorphic variable drainage density (Fig. 7.6). This relation yields the least squares equation of:

$$b_1 = 1.366 - 1.80\ D_d \qquad (7.3)$$

where: D_d = drainage density in ft/ft^2

b_1 = a measure of non-linearity based on slope of relation between intensity and lag time

This equation has a correlation coefficient of -.99; thus, explaining 98 percent of the variation in data.

Drainage density is a geomorphic macro-variable. That is, it represents a mean condition in the basin, and it has a functional relation with many descriptors of internal characteristics of the basin. The mean length of overland flow is an example of one of these. Taken as one half the inverse of the drainage density, this mean overland-flow length increases directly with increases in non-linearity. Such a relation suggests that the greater the overland flow component the greater the violation of the assumption of linearity.

Peak Rates of the IUH

The time to peak (t_p) of the IUH model derived by Nash is calculated by:

$$t_p = (n-1)K \qquad (7.4)$$

where n and K are as previously defined. Substituting this relation for time to peak in Equation 7.2 the peak rates of the IUH (h_p) can be determined as follows:

$$h_p = \frac{(n-1)^{n-1}\ e^{-(n-1)}}{nK} \qquad (7.5)$$

This peak rate is an index of the efficiency of the geomorphic system to evacuate the rainfall from the system. The higher the peak rate the more efficient is the system.

In the data set for which relief is constant (set 2, subset 3), as drainage density increases the efficiency of the system increases (Fig. 7.8). This

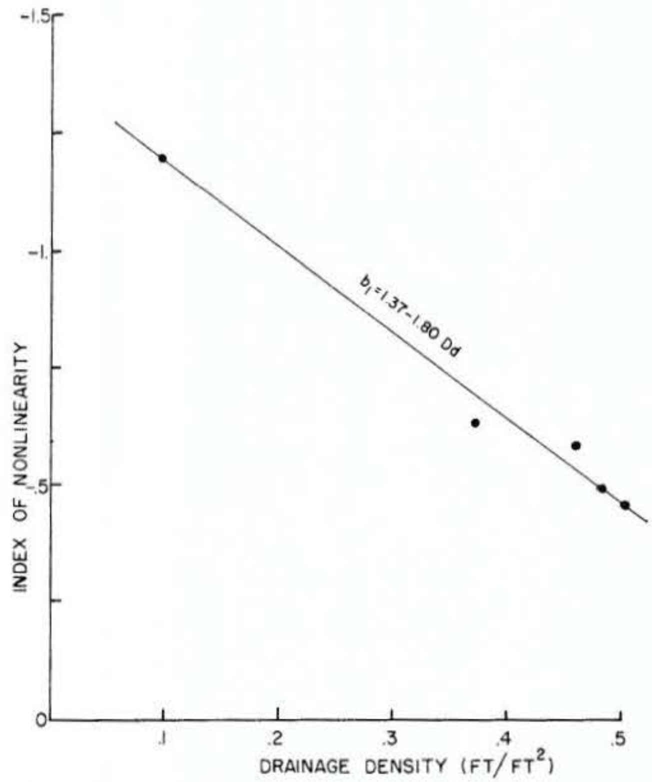

Fig. 7.6. Changes in the index of nonlinearity (slope coefficient of the linear regression relation between rainfall intensity and the lag time of the instantaneous unit hydrograph) with changes in drainage density for each network in set 2, subset 3.

occurs for all rainfall intensities. This relation is curvilinear as shown by the lines drawn through the data by eye. It suggests that little change in efficiency is obtained for increases in drainage density up to a value near 0.4 ft/ft^2, but subsequent increases produce greater increases in the hydrologic efficiency of the system.

Again the three lower values of drainage density are derived from an abstracting system in which divides are being concurrently lessened with decreases in drainage density. This is also seen as a modifier of hydrologic efficiency. Thus, the arrows drawn on Figure 7.8 show the direction of the geomorphic evolution of the basin. However, this relation cannot be used to describe the efficiency of the basin during extension. Perhaps, during extension the curves would be shifted to higher values. This would result from steeper inter-channel areas as channels degraded. However, what the changes would be with a large segment of undissected upland, is unknown.

The relations suggest that the changes in hydrology resulting from changes in basin form are complex. Variables, such as drainage density, do not properly index modifications of the hydrologic response of the basin. That is, in an abstracting system areas of overland flow change significantly in terms of their slopes and infiltration characteristics but this is not reflected in the drainage density variable.

For a given drainage density the higher the input rate of rainfall the more efficient is the system (Fig. 7.8. Whether this is totally a result of the experimental design is unknown, but it is reasonable to expect larger flows of water to utilize the channel

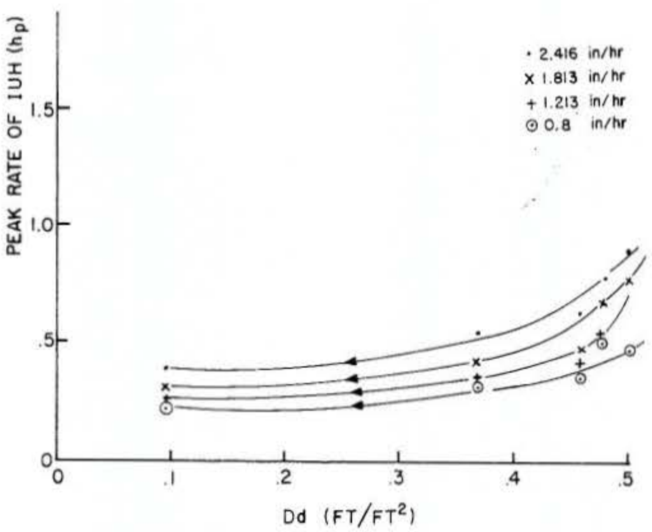

Fig. 7.8. Changes in the peak discharge rate of the instantaneous unit hydrograph (IUH) as a measure of hydrologic efficiency with changes in drainage density (Dd) for each precipitation rate available. Networks are on one baselevel and arrows show direction of network evolution (set 2, subset 3 data).

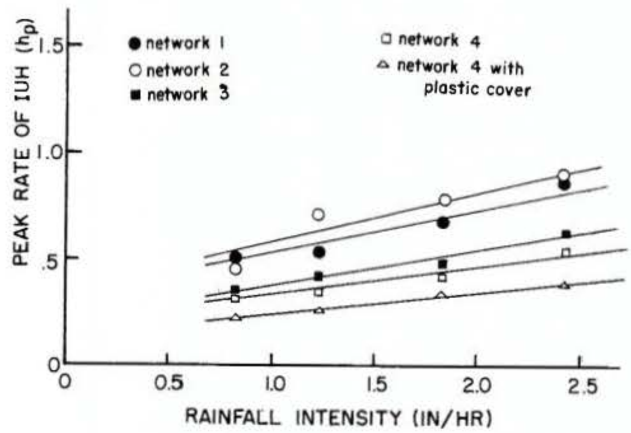

Fig. 7.9. Changes in the peak discharge rate of the instantaneous unit hydrograph (IUH) as a measure of hydrologic efficiency with changes in rainfall intensity for networks on one baselevel (networks from set 2, subset 3).

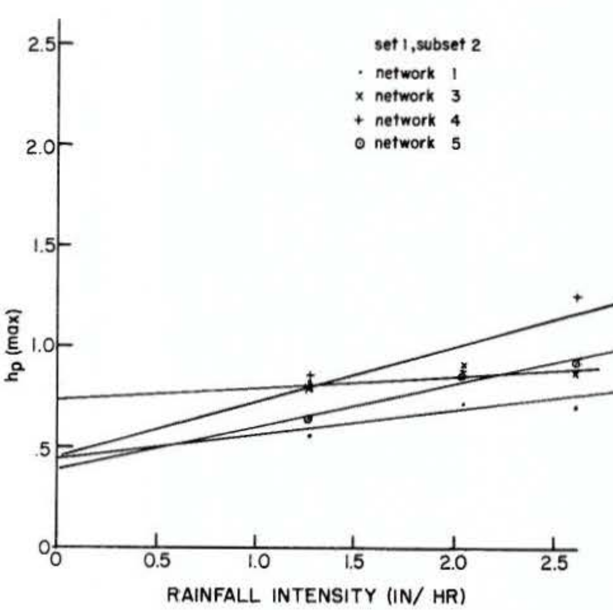

Fig. 7.10. Changes in the peak discharge rate of the instantaneous unit hydrograph (IUH) as a measure of hydrologic efficiency with changes in rainfall intensity for networks with both relief (baselevel change) and drainage density changes (networks from set 1, subset 2).

more efficiently. Utilizing rainfall intensity as the independent variable (Fig. 7.9) reveals a linear relation. The slopes of the given regression lines are not significantly different from one another when compared by a t-test. Thus, increase in efficiency with an increased rainfall intensity is similar for all drainage densities given.

The relation between rainfall intensity and the peak of the IUH for the hydrologic data from set 1, subset 2 with increases in both relief and drainage density again show increased variability of the data due to the wind (Fig. 7.10). Because of this variability little can be said in comparing the two experiments. The overall trend of an increased efficiency with increased precipitation intensity is apparent for a given drainage density but whether the efficiency increases in response to increases in relief and drainage density cannot be determined.

Although the variability is high, it is interesting to note that the mean regression coefficient for the 3 equations in Figure 7.10 (changes in both relief and drainage density) is .20 with a standard deviation of .09. The same regression coefficient for the five equations in Figure 7.9 on one baselevel is .17 with a standard deviation of 0.05. This results in a 15 percent difference and considering the standard deviation is probably not significant. Thus, the slopes of the regression equations would appear equivalent. This suggests that changes in drainage density aside, an increase in precipitation rate produces a nearly constant increase in the efficiency of the basin.

The mean value of the peak of the IUH (h_p) for the hydrographs generated on the basin with changes in both relief and drainage density (set 1, subset 2) for all intensities and networks (Fig. 7.10) is 0.42 with a standard deviation of 0.04. The mean value of h_p for all intensities and networks in set 2, subset 3 (Fig. 7.9) is 0.24 with a standard deviation of 0.09. This results in a 43 percent difference in the means of h_p between the two experiemnts and suggests that the hydrographs generated on the extending network with changes in both relief and drainage density are more efficient overall.

Although relief is continually increasing, the first network has a relief of only 0.985 and although the drainage density is high there is a considerable portion of the upland area which has not, as yet, been dissected. Thus, overland flow is still significant. Because of the variability of the data in set 1, a complete analysis is not possible. Of interest is whether a developing basin with a large undissected area at the headlands and channels concentrated near the outlet is as efficient as an abstracting system in which the drainage density is the same but channels are developed throughout the system. The data suggest that the developing basin is more efficient even though the relief is lower.

Of particular interest is the comparison of the two experiments at maximum extension. The data from Figure 7.9 and 7.10 have been replotted for the two networks which represent maximum extension for the respective basins (Fig. 7.11). The data are remarkably similar, although drainage density is 34 percent greater in set 1 and has a 17 percent greater relief. The similarity is due to the fact that the basins have both been filled by the network. Although there is variability in the set 1 data, it would appear greatly fortuitous for experimental error to produce such a close relation. Such similarity suggests that a maximum efficiency in a basin is reached dependent on the relief and drainage density, but increases in efficiency beyond this maximum do not occur with continued increases in relief or drainage density.

This idea, certainly not fully documented, would seem to be in opposition to the point of view that the most efficient means of evacuating unconcentrated runoff from a basin would be for the total basin to be composed of infinitesimally short slopes each leading down to a basal stream channel (Chorley and Kennedy, 1971, p. 235). Maximum efficiency of water evacuation would probably be attained long before this theoretical basin was developed.

The reason for a maximum efficiency is not clear. Perhaps as drainage density increases the complexity of the channel system becomes so great that evacuation of the water from the basin is slowed by the circuitous paths the water takes to the outlet.

To summarize these observations on changes in efficiency during basin evolution, consider a basin that initially has no drainage density but, rather, is two intersecting planes that allows drainage to the outlet. One change in baselevel initiates a channel network which grows to maximum extension and then begins to abstract. Following the observations made on the experimental data the hydrologic efficiency of the system may evolve as shown in Figure 7.12. As the network grows, drainage density progresses from initiation, to extension, to maximum extension and is shown by the solid line. The hydrologic efficiency before network gorwth (the Y-intercept) is at some low value, but it is greater than zero. As drainage density increases, the efficiency (h_p) increases as the basin evolves to maximum extension. During abstraction, the drainage density declines and efficiency declines. The abstracting curve, identified by the dashed line, shows that an abstracting system has less efficiency than an extending system at the same drainage density.

It is assumed that if this model were made more complex by incremental increases in relief during the network evolution (lowering of baselevel) that the curve would no longer be smooth, but it would reveal step increases in efficiency at the drainage density values at which relief was changed.

Summary

The hydrologic sensitivity of the experimental facility was identified, and it is evident that the facility is capable of producing minor hydrographic differences, which can be observed with the procedures used, particularly after the facility was enclosed.

In light of the sensitivity of the system, it is unfortunate that both relief and drainage density were allowed to vary during experiment one. Although satisfactory from a geomorphic standpoint, not holding relief constant did not allow adequate hydrologic comparison with the second data set.

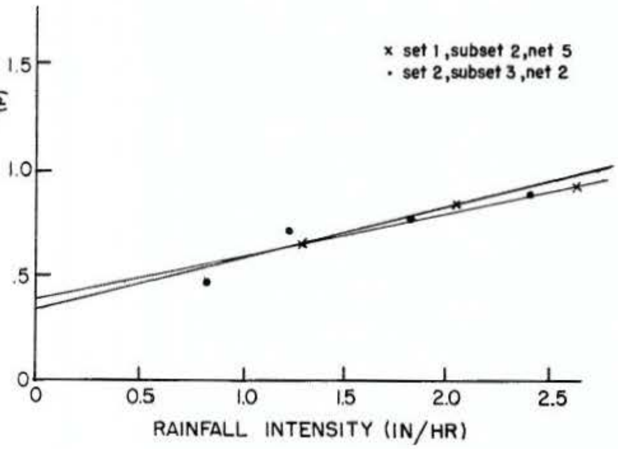

Fig. 7.11. Comparison of relation between peak discharge rate of the instantaneous unit hydrograph and rainfall intensity for the hydrographs produced on the networks at maximum extension for both experiments.

In examining the hydrologic response to both an increase in basin relief and drainage density, the rate of peak discharge to the equilibrium discharge or rainfall input rate (Q_p/Q_e) was seen to vary directly with these geomorphic parameters. As used as a rough form of basin efficiency, the Q_p/Q_e ratio indicated that, as relief and drainage density increased, the efficiency of the basin to evacuate water increased. When using the peak of the IUH as an index of efficiency, the direct relation between the efficiency and increased rainfall was again noted but the increase in efficiency with increasing drainage density and relief was not so straightforward. If there was a direct relation between efficiency and the geomorphic parameters, the regression lines in Figures 7.10 and 7.11 should be nested in relation to their ruggedness number with the lowest ruggedness number on the bottom. Such is the case in experiment 2 (Fig. 7.9). In experiment one, however, the sequence begins with the basin with the lowest ruggedness number but does not progress through the higher values (Fig. 7.10). Two reasons are apparent. One, the experimental error inherent in this data set and, two, the small change in efficiency (h_p) at progressively higher values of the ruggedness number.

The hydrologic efficiency of both experiments at maximum extension are almost the same. This results even though drainage density is considerably higher in set 1. This suggests that continued increases in the drainage density for a similar relief will not increase efficiency of the hydrologic response. Indeed, continued increases in drainage density may possibly result in loss of efficiency. This could result from an increase in the distance and circuity of the path of a particle of water, as the drainage density becomes more complex.

The Q_p/Q_e ratio had a dramatic increase between the ruggedness numbers of 0.348 and 0,856, with further increases in the ruggedness number. The peak of the IUH showed a similar response if one ignores one data point. Thus, efficiency increases early in the development of the basin. This may be a result of the large undissected area on which overland flow must occur early in the development.

Peak sediment yields followed closely the Q_p/Q_e ratio relation with a similar non-linear response.

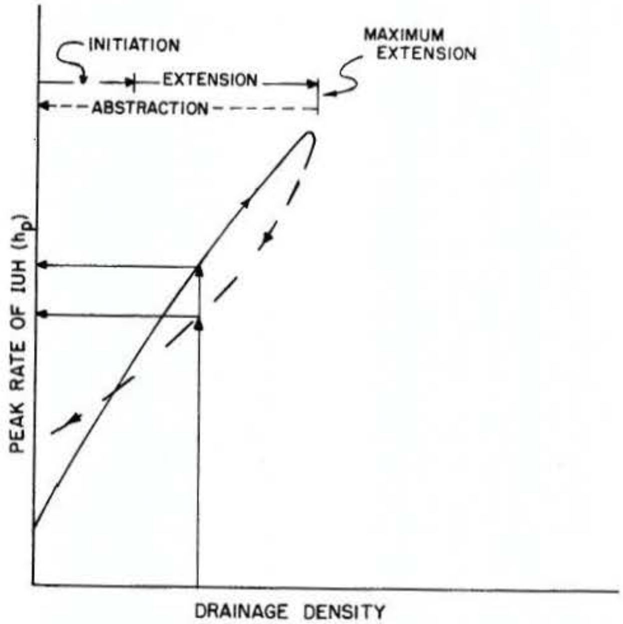

Fig. 7.12 Hypothetical relation between basin evolution and hydrologic efficiency as as indexed by the peak discharge rate of the instantaneous unit hydrograph. Arrows on the curve show the direction of network evolution through extension and into abstraction.

More data are needed on the upper and lower ends of the relations to identify trends at the limits.

Lag time from Nash's model was used to derive an index of non-linearity of the system. Drainage density is a macro-variable indexing many hydrologic properties of the basin. These results were obtained from a system which was primarily abstracting, although it is interesting to note that network 1 in this series was still extending and fits the relations well. Thus, the question of differences in non-linearity in an extending and abstracting system are still unresolved.

If with an increase in drainage density there is an increase in relief, the non-linearity of the basin appears to become more stationary. In nature, these two variables interact so that deviation from linearity may not be severe as long as both variables are free to change. Changes in drainage density alone, however, produced a more significant change in the linearity of the system. As drainage density increases, the non-linearity of the basin decreases (Fig. 7.6). Changes in drainage density without changes in relief occur by man's modification of the basin. Thus, the change in the hydrologic response of the basin with changes in drainage density alone is significant.

Within these experiments a change in relief resulted in a change in drainage density. Thus, relief was an independent variable influencing drainage density. In nature, both relief and drainage density are dependent variables and lithology is an independent variable. Changes in vegetative cover or micro-climate can, however, result in transformation of relief and drainage density. Therefore, in the field a variety of variables can change simultaneously and all affect the hydrologic response. In these experiments only hydrologic changes resulting from modifications in the morphology were identified.

As drainage density and relief begin to increase, the efficiency of the hydrologic response increases. This is to be expected. Overland slopes increase and the effect of gravity becomes greater. The channel system is expanding and this system is the more efficient method of evacuating water from the basin. However, with continued increases in drainage density, hydrologic efficiency does not continue to increase. At higher drainage densities the hydrologic efficiency decreases. The same amount of precipitation falls over a larger surface, more small channels carry water which have a high degree of roughness, and the channel system becomes more intricate which results in a particle of water taking a longer path to the outlet. All these factors contribute to a loss in efficiency. Therefore, hydrologic response reaches a maximum efficiency which begins to decline as drainage density increases. Although not tested here, sediment yield, highly dependent on the hydrology, may react in a similar manner.

Because this was a first investigation in a new facility, many questions have been generated and few resolved. Certainly, the facility appears capable of testing many hypotheses and answering the following questions:

1. Is there a maximum sediment rate from a basin? Is there some value of drainage density and/or relief at which sediment yields begin to increase significantly? If such a point exists, its determination would help in identifying how severely a basin could be modified before large changes in sediment yield would be expected.

2. At a given relief and drainage density, are there differences in the hydrologic parameters between an extending and abstracting system and if so, how can these differences be detected?

3. If a network has reached maximum extension in the basin, is the efficiency maximized even if the drainage densities are substantially different?

4. Drainage density has a functional relation with length of overland flow, slope of overland flow, stream order, and other variables which could be examined as to their relation with hydrograph response.

Perhaps one of the most basic questions in the area of synthetic hydrograph generation is not hydrologic but geomorphic. That is, what is the functional relation among geomorphic parameters? One of the best ways to identify dependency is to examine the variables in time as has been done here. Thus, there is a definite relation between relief and drainage density but the question of how this relation changes with different material type remains unanswered. A further example is the bifurcation ratio which has been shown to be extremely stable after the initial network growth. Such a stable parameter would not appear to be useful as a hydrologic predictor because of its constancy.

CHAPTER VIII

CONCLUSION

Experimental techniques have been used only sparingly in geomorphic research. However, they offer exciting possibilities to extend the understanding of geomorphology both in the laboratory and in the field. This is particularly true of research on processes in fluvial problems where rates of erosion and aggradation are slow and determination of relations may take many years of field investigation.

Experimental geomorphology offers the ability to generate data rapidly and to study intensively the processes in the development of land forms with some variables held constant. Thus, the focus in these studies is on geomorphic processes, their rates and interaction.

Using the experimental approach to examine the evolution of a total drainage basin presents some difficulties. These problems are associated with scaling ratios, boundary conditions, and initial conditions. The major problems are nearly eliminated by using a facility large enough to be considered a prototype basin.

Overall evolution of the drainage system can be indexed through time by drainage density. Drainage density showed an increase to a maximum and then a decline (Fig. 3.1). The evolution was related to Glock's (1931) classification of drainage evolution and to his categories of initiation, extension, and abstraction. The differentiation of extension and abstraction occurs at maximum drainage density which is termed maximum extension.

Glock separated his categories on the basis of the processes active within the basin. It was found, however, that processes overlapped. Abstraction began near the mouth of the basin during extension, but extension continued to be the dominant process. Thus, the point of maximum extension is the stage of evolution at which the dominate process changes from extension to abstraction.

Differences in initial slope and baselevel change resulted in differences in the drainage density both at initial mapping and at maximum extension. These differences were related to two modes of growth. The first mode of growth was termed "headward growth" and was produced on an initial surface slope of 0.75 percent with an initial baselevel change. The other growth mode was termed "Hortonian growth" and it developed on an initial surface of 3.2 percent slope with no baselevel change.

A third experiment on a slope of 12.2 percent with a baselevel change produced growth characteristics like the headward growth model, although the network had extended further into the basin. Hence, lowering of baselevel tends to initiate "headward growth" whereas no lowering of baselevel tends to produce "Hortonian growth." The slope of the initial surface determines the rapidity of growth of the network.

Headward growth is characterized by the network developing headward and developing completely as it grows. That is, there is little internal growth and rearrangement within the network, as extension progresses. Headward growth was reflected by:

1. no significant change in the geometric mean length of first-order streams through time
2. remarkably consistent first-order stream length log-normal histograms
3. changes in the stream length when plotted against stream order. Higher order streams were initially short but became longer as the network grew into the basin.

Hortonian growth is characterized by the initial blocking out of a large segment of the watershed by a skeletal network. Later development continues by internal growth of small streams within the skeletal network. Rearrangement of the network during initial development was also identified. Channels shifted to other tributaries or were eliminated. Hortonian growth was reflected by:

1. a significant change in the geometric mean length of first-order streams. First-order streams were initially very long as they were involved in the "blocking out" process, but they became shorter, as additional streams branched from these initial channels.
2. first-order histograms initially were rectangular with a wide range of length values. Later, histograms became log-normal, and they lost the longer channel lengths.
3. a straight line relation for stream lengths when plotted against stream order. Because the initial network grew rapidly over a large portion of the basin, higher order streams developed longer lengths early in their development.

The "blocking out" of a skeletal network, characteristic of the Hortonian growth, seemed to alter the internal growth of channels which developed later on the network evolution. Figure 4.1 shows the smaller number of channels that developed by maximum extension during Hortonian growth. A small value of drainage density (Fig. 3.1) is also characteristic of Hortonian growth. Such a reduction in number of streams, and drainage density suggests that the initial "blocking out" of the watershed by the skeletal network effectively changes the competition for available area, which in turn reduces the number of streams initiated. Thus, the type of growth pattern followed can change the ultimate drainage density at maximum extension.

The importance of competition among channels and their associated basin areas cannot be overestimated. In the field consistency of network form for a given geology has been identified. This consistency must be related to certain conditions which yield a uniformity in channel competition. Although initial conditions are impossible to identify in the field, they provide a mechanism in an experimental situation to examine competition. Hypotheses on how competition is altered must ultimately be transferred to computer models of network growth to amplify the understanding of the growth processes.

The remarkable similarity of first-order length histograms, in the first experiment, the tendency for first-order histograms in the second experiment to approach the characteristics of the first experiment, and the stability of the geometric mean length of first-order streams in the first experiment point to a deterministic component in the growth of the networks. The marked regularity suggests a range of lengths of first-order streams at which bifurcation occurs. Unfortunately this range could not be determined but the marked regularity suggests a strong deterministic component in channel growth.

Computer simulation models developed to date are not satisfactory because they do not have an identifiable deterministic component, nor driving variables (e.g., relief) which influence the network. Several models have been proposed which can be related to the headward growth model and use a Monte Carlo approach. A more satisfactory approach would be the use of Markov chains in order that both random and deterministic components can be utilized.

The emphasis in computer simulation to date has been the random component in the network growth process. A deterministic component must also be included to reflect the regularity noted in these experiments. Further advances in stream network modelling should incorporate such variables as relief, geology, and land cover in order that response in network growth to alteration of these variables can be accomplished. This will allow changes in the rate of network growth and, therefore, incorporate nonstationarity.

Sediment samples were obtained as the basin evolved. Sediment yield through time on a baselevel can be described as an exponential decay (e.g., Fig. 6.1 and 6.3). Sediment yield is high initially and declines through time as network growth declines. During late stages of growth on a baselevel, sediment yields are maintained at a minimum value by rainsplash.

During experiment 1 with an initial change in baselevel, sediment yields were initially high, but they declined rapidly. In the second experiment with no change in baselevel the initial sediment yields were not as high, but they maintained higher values during later evolution. Such a difference is directly related to the initial conditions, but can also be related to the two growth models. In headward growth the network grows completely as it migrates headward. The initial high sediment yields are due to the knickpoint being close to the sampling station (the outlet). As growth continues, the major channels develop rapidly and can store sediment from upstream which results in a decline in the sediment yields. Continued evolution brings a regular decline in the growth of channels and a continued decline sediment yields.

During Hortonian growth, initial channels develop rapidly, but they are not well developed. Alluvial deposits appear at the mouths of tributaries, and the network cannot flush the sediment being produced. Channel extension occurs by small multiple knickpoint migration within the basin. Thus, the sediment produced cannot be readily transported to the basin outlet, and measured sediment yields are not initially as high. Internal growth, rearrangement of channels, and the increased efficiency of the channels to deliver sediment to the outlet with time help to maintain higher sediment yields during the later part of extension.

On a particular baselevel, where the evolution continues through extension and into abstractions, the overall exponential decay of sediment yield is noted. However, two additional features of the sediment record are (1) the overall variability of the data and (2) the emergence of cycles or periods of increased variability.

The sediment yields, collected during the experiment, simulate long-term basin evolution. That is, the overall exponential decay represents geologic time. Therefore, superimposed on the overall curve would be short-term cycles (5 to 100 years) induced by changes in climate, vegetation, or man-induced modifications. These short-term cycles also would have an inherent variability.

It is disconcerting to see such a large variability in the long-term record where precipitation and land cover characteristics are held constant. Certainly, such variability must be amplified in the field. Sediment stations, established in the field, attempt to predict short-term trends in sediment yield. Any such trends are masked by the variability resulting from (1) the long-term sediment yield, (2) short-term sediment measurements, and (3) measurement error. Each of these sources of variability may be as great as 100 percent and all three sources may be additive for a particular measurement. Therefore, an individual sediment measurement is highly suspect, a large number of measurements are needed to define a trend, and, finally, even with a large number of measurements trends may be obscure.

Although sediment yield is measured at a point, sediment production cannot be determined as easily because it varies in both time and space. An approximation to sediment production can be obtained by observing knickpoint migration. The migration of a knickpoint up the network occurs in a regular manner with respect to Strahler order of the stream. Thus, as erosion progresses upstream, the number of channels increases geometrically, which produces an increase in sediment production. As erosion continues upstream, smaller sub-basin areas are encountered which slows sediment production. There two factors interact. Where the two factors are maximized, sediment production is maximized. This results in a sediment production curve which increases to some maximum and then declines through time (Fig. 6.12). This is much different from the sediment yield curve plotted on the same curve (Fig. 6.12). It is suggested that the periods of extreme variability in the sediment yield curves is produced at the time of maximum sediment production. This maximum produces significant increases in the sediment load delivered to the main channel, which stores and flushes the excess alluvial material creating the variability.

Examining the main channel during this period of change in sediment production and sediment yield suggests the following sequence. First, the main channel degrades as the knickpoint migrates upstream and the channel is narrow and deep. Second, an increased sediment load from upstream results in the main channel widening, braiding, and depositing sediment. Third, the decline in sediment production upstream results in the main stream incising into the previously deposited alluvium. This sequence has been termed complex response (Schumm and Parker, 1973) and suggests that degradation initiated by a baselevel change produces a period of aggradation followed by renewed incision.

The storage of sediments in the channel has been recognized. However, neither the extent nor the storage time of sedimentary deposits is predictable at present. Wolman and Schick (1967, p. 459) suggested that the channel in the upper part of a watershed disturbed by the construction of a major interstate required seven years or less to clear itself of the stored sediment. Meade and Trimble (1974) reported on a larger stream system in the Atlantic drainage. Sedimentary deposits on the channel were derived from changes in land use and poor soil-conservation practices. Decreases in sediments to the channel have occurred since the 1930's. Sediment stored in the channel is continuing to be removed. Thus, the length of time to clear these channels of sediment is greater than 45 years. Therefore, size of the basin is a factor in the length of time necessary for stored sediment to be cleared from the channels.

Measuring the storage and flushing of sediment from a basin will be difficult because of the variability of the data. However, in order to monitor basins which have been modified by man, it is important to determine if the cyclic phenomenon can be identified in the field and, if so, to determine the magnitude of these cycles and to determine the periods (time) between the cycles.

One minute rainfall duration hydrographs were run at four different intensities on some of the mapped networks. It was found that the ratio of peak discharge to the equilibrium discharge (input intensity) increased as the ruggedness number (drainage density time relief) increased. This ratio was not as great for the lower intensities which suggests that the geomorphology of the basin affects runoff from lower rainfall intensity events to a greater degree than high intensity events. The Q_p/Q_e ratio shows a dramatic increase during early basin development or with lower values of the ruggedness number. Part of this large increase at these lower values may be due to the reduction of large undissected areas which may be characterized as having overland flow.

The peak sediment yeild derived from the hydrographs with a one minute rainfall duration follows the same relation as the Q_p/Q_e ratio with respect to the ruggedness number. That is, the peak sediment yield shows a very strong dependence on the amount of water delivered to the outlet.

Efficiency of the basin was indexed by the peak of the instantaneous unit hydrograph (IUH). This showed that as precipitation increased the effeciency of the channel system increased. At maximum extension in both experiments the peak of the IUH was nearly the same. This resulted even though experiment one had a higher drainage density. Thus, it would appear that continued increases in drainage density to not produce continued increases in the hydrologic efficiency of the system. Efficiency is not increased above some maximum and this maximum is associated with maximum extension.

Lag time of the IUH was used as an index of linearity of the hydrologic system. In a truly linear system no change in lag time with changes in precipitation rate is expected. Thus, deviations from a horizontal line on such a plot can be used as an index of system linearity. It was found that as drainage density increases, the linearity of the system increases. However, if both drainage density and relief vary the non-linear component remains somewhat consistent.

Linear methods for determining hydrograph response have been used almost exclusively in the past. However, several non-linear methods have been proposed and will be used to a greater extent in the future. Better techniques for determining which method to use need to be established. From this research it is seen that if the basin has a high drainage density, linear techniques are adequate. If the basin has a very low drainage density, such as a parking lot, a non-linear technique should be used.

There remains the unanswered question of what differences there are in the non-linear component between an extending and an abstracting network. Also, these changes in linearity were identified with the geomorphic macrovariable drainage density. The question remains, what is the effect in terms of internal variables such as length and slope of overland flow.

It would appear that non-linear influences are derived primarily from overland flow. If a significant channel system is available, the system becomes more linear. This suggests that small experimental studies of hydrologic response, in which channel systems cannot effectively modify the non-linear component, will produce a more severe nonlinear component than found in larger natural basins.

The ability to detect small changes in hydrograph response allows further experimental work in the interaction between geomorphology and hydrology in the REF. Future work must concern itself with two problems. One, many geomorphic variables interact (e.g., relief and drainage density) and the extent of dependency is not fully understood. Experimental design must identify these dependences and the problems created by holding certain variables constant. Certainly, the power of experimental techniques lies in the ability to hold variable constant but the impact on other variables allowed to change may be difficult to ascertain. This impact may be particularly difficult to identify if attempts are made to extrapolate derived relations to the field.

Second, some variables do not change significantly as the system evolves, and this suggests that these variables cannot index geomorphic evolution nor predict changes in the hydrologic response. For example, stream number relations (e.g., bifurcation ratio) are fairly stable through time and suggest that these stream number variables are primarily related to the topology of the network. Examining variables through basin evolution provides an index to how well geomorphic variables depict basin evolution.

The power of experimental procedures lies not only in determining rates of change but also in determining relations at extremes. The response of the basin to minimum and maximum values of a particular variable are important. For example, sediment yeilds may change but little as drainage density is altered at the lower values but increases in drainage density may produce significant changes in sediment yields at the higher values. The ability to detect these threshold values at which basin response is significantly altered would be of value in predicting response to man-induced basin modification.

Even though the REF is small and intensively monitored, basin response is complex and the identity of a particular relation depends on an adequate experimental design. However, the experimental approach appears the best method to obtain quickly answers to many geomorphic problems. In particular, the relation between sediment yield and sediment production needs further work. The identification of the mechanism of sediment storage is a basic problem in gromorphology.

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APPENDIX A

NETWORKS MAPPED IN THE STUDY

Network 1
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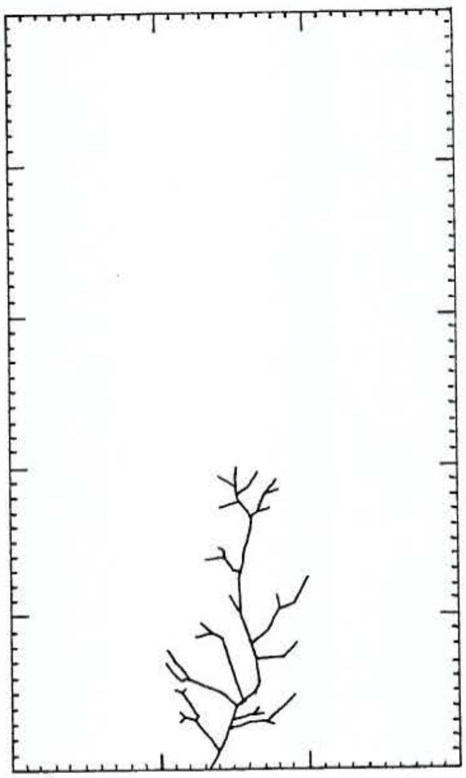

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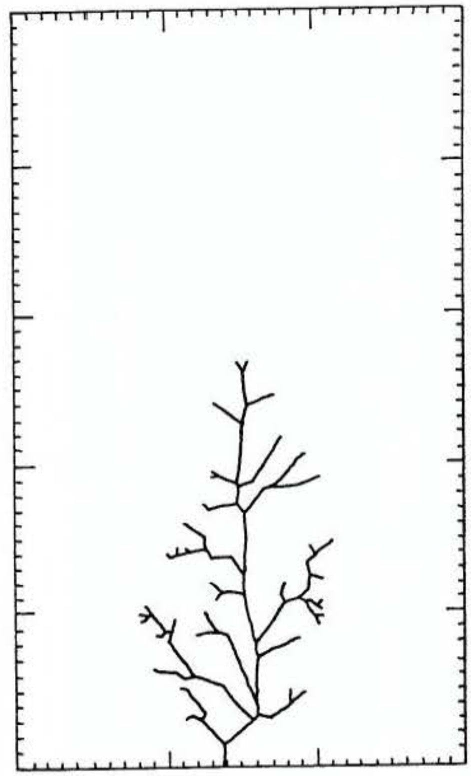

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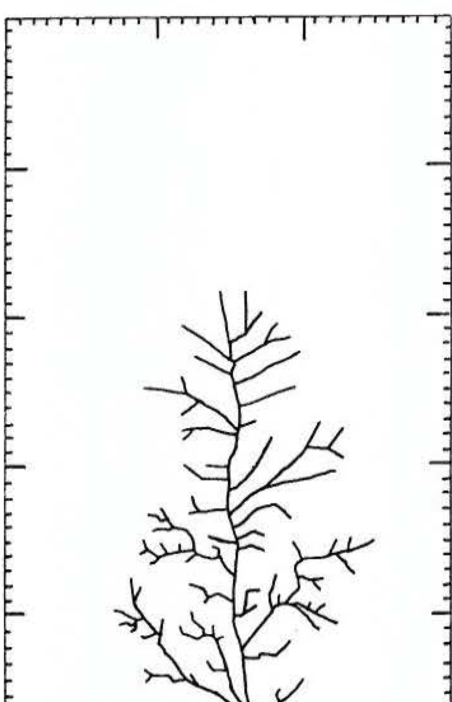

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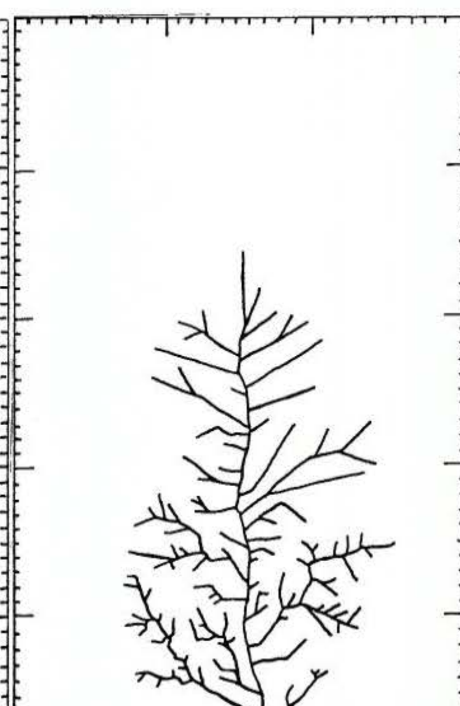

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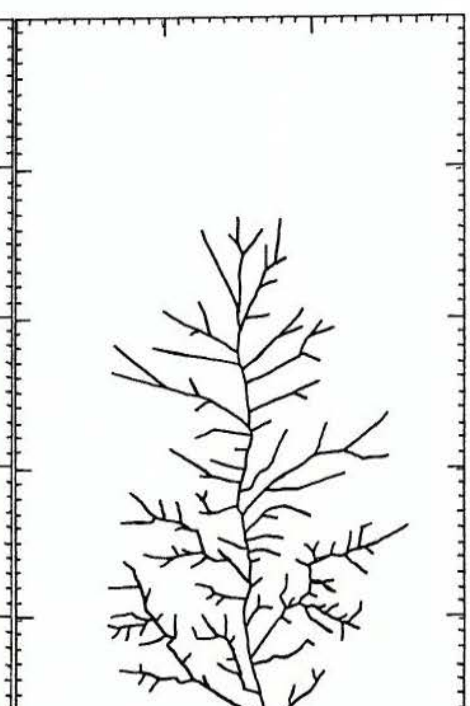

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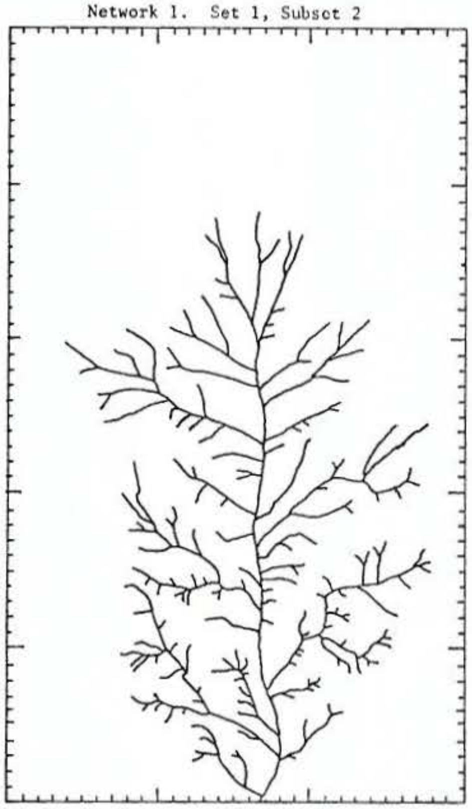

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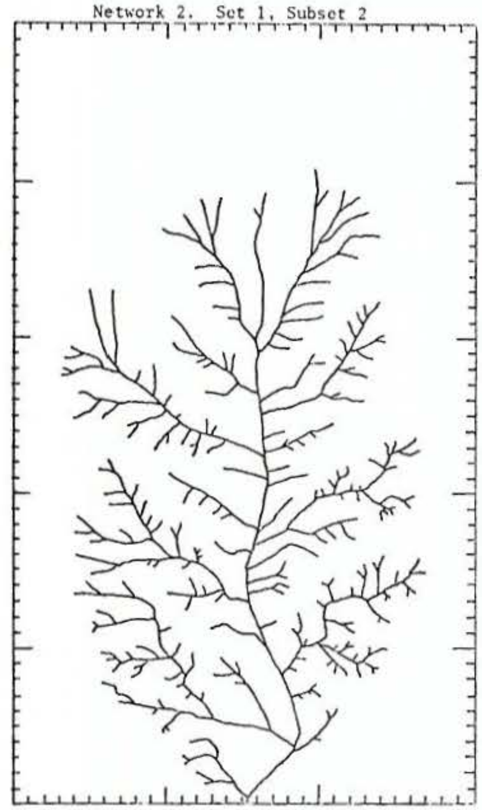

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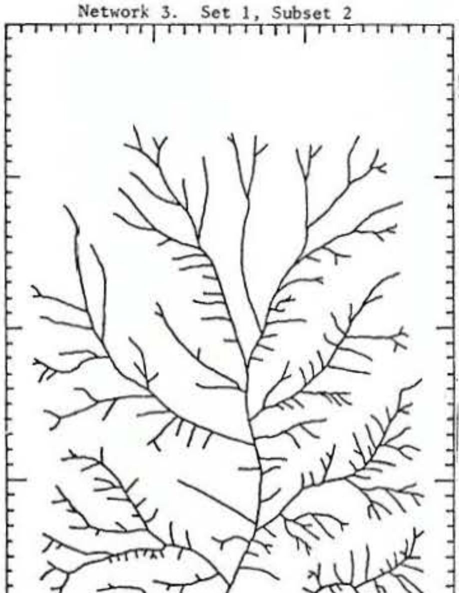

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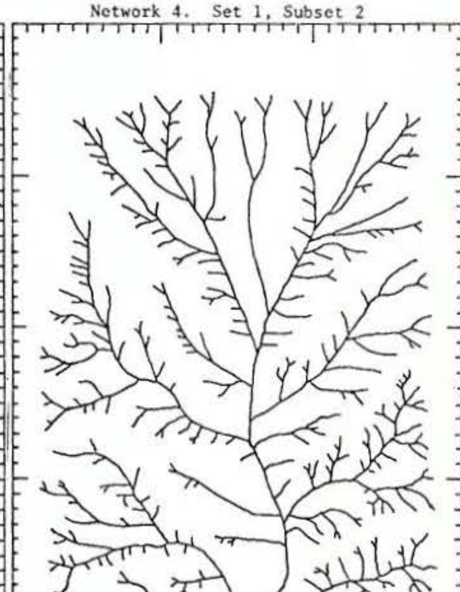

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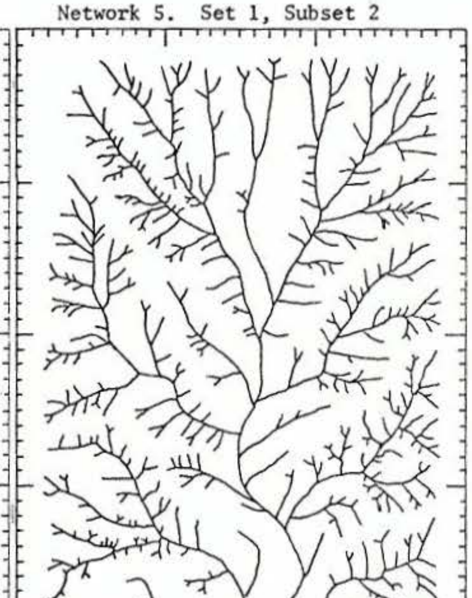

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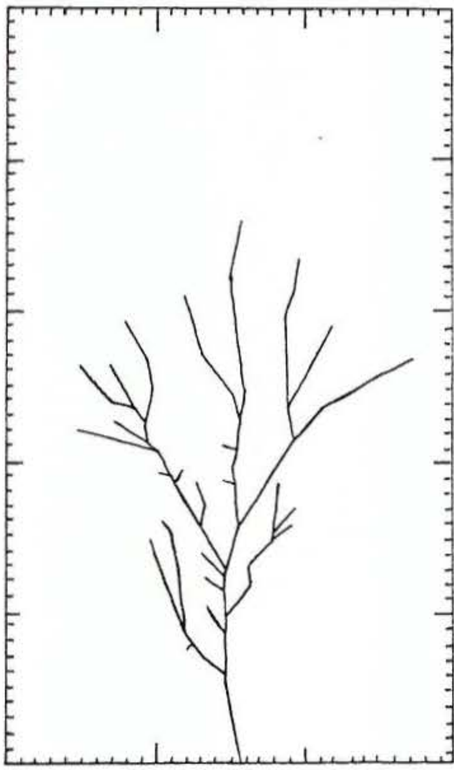

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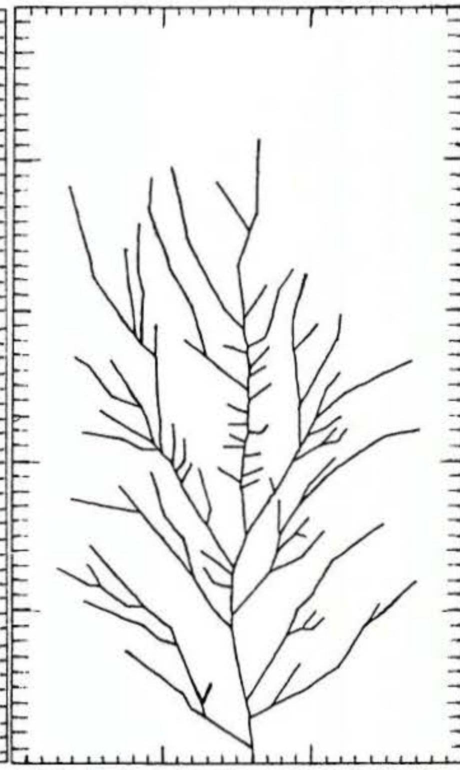

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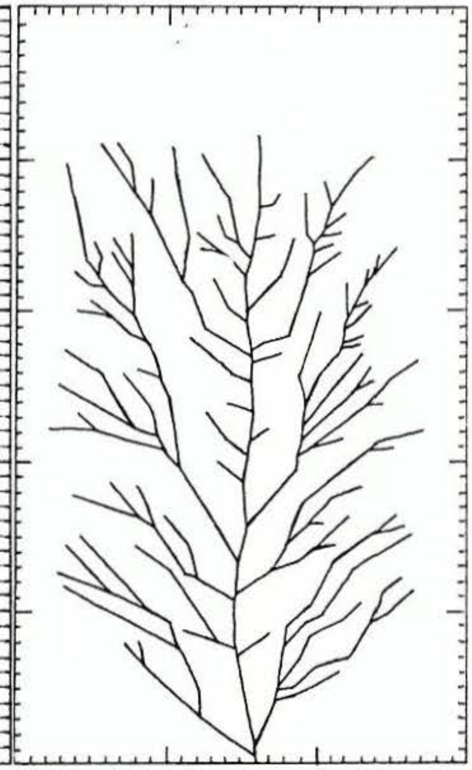

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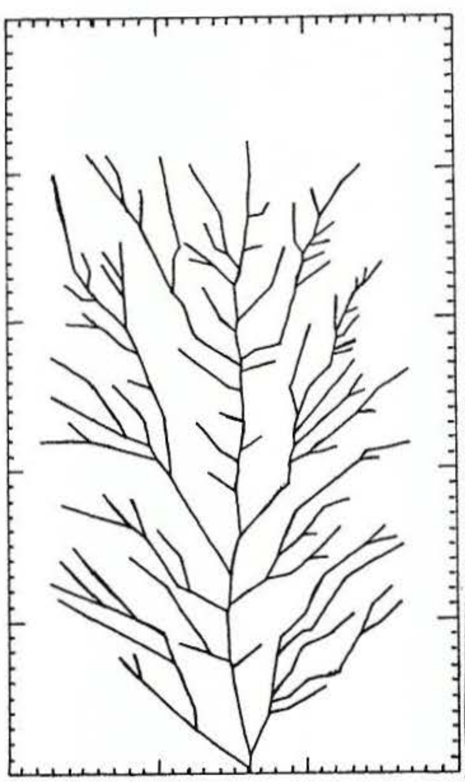

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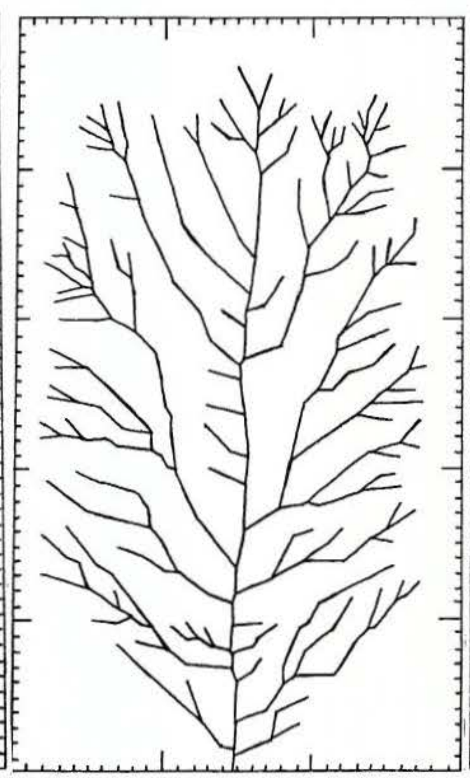

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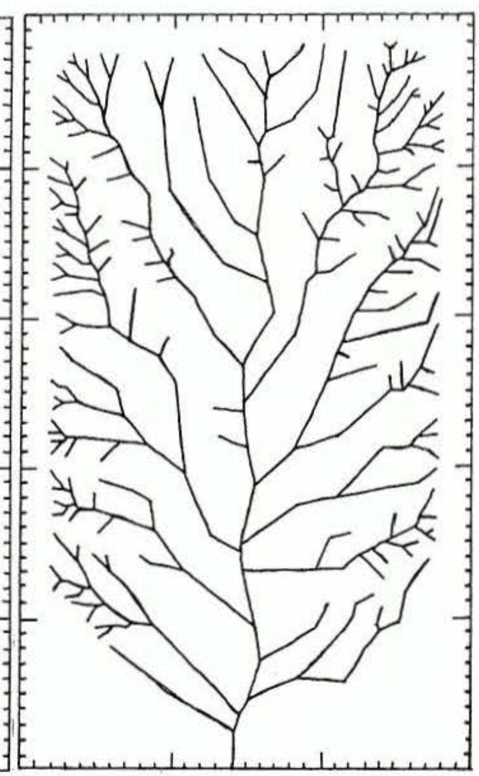

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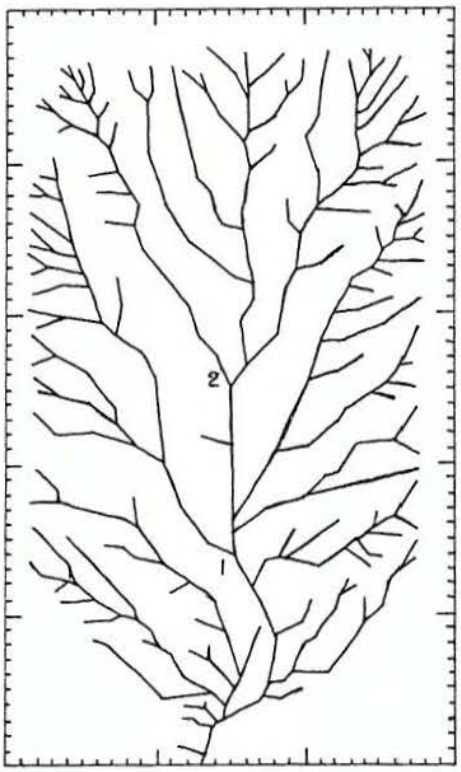
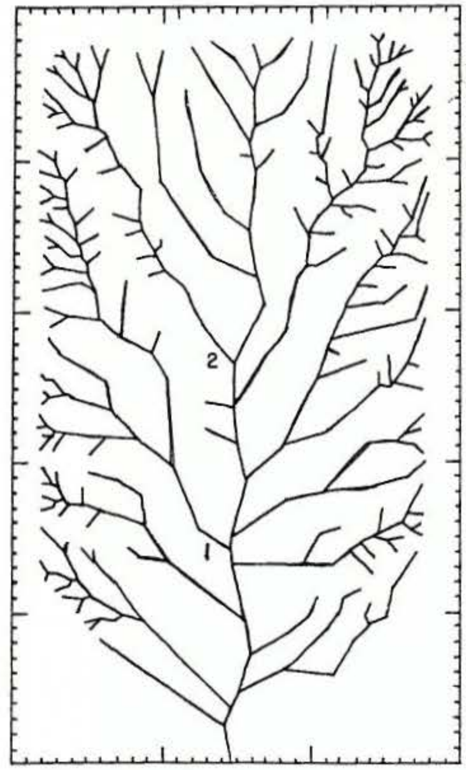
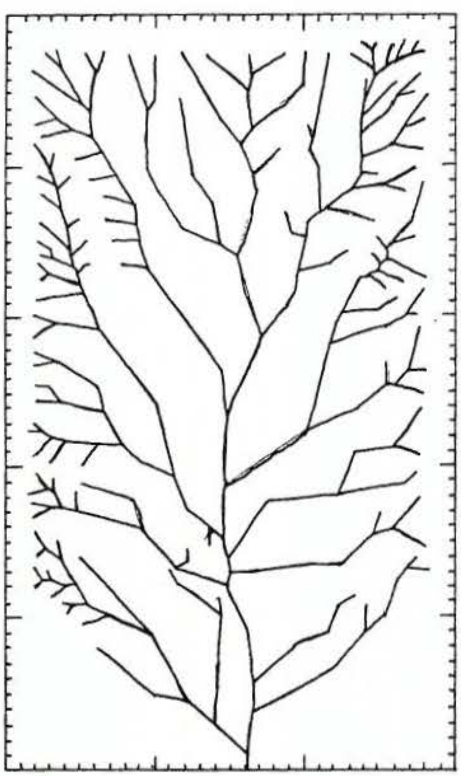


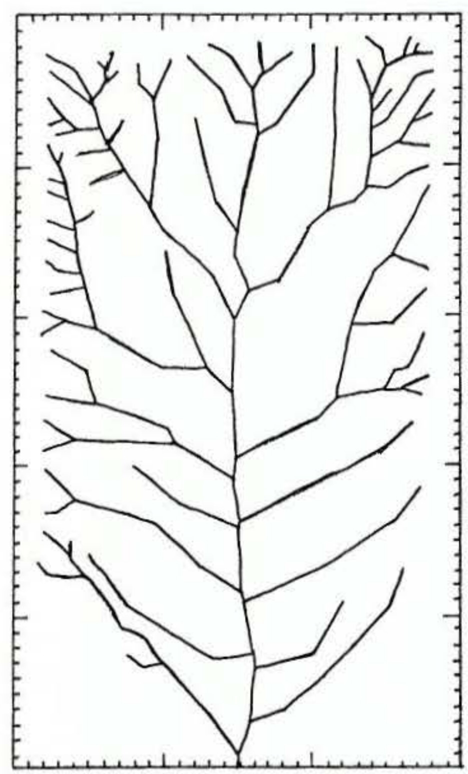
Network 2
Set 2, Subset 3



Network 3
Set 2, Subset 3

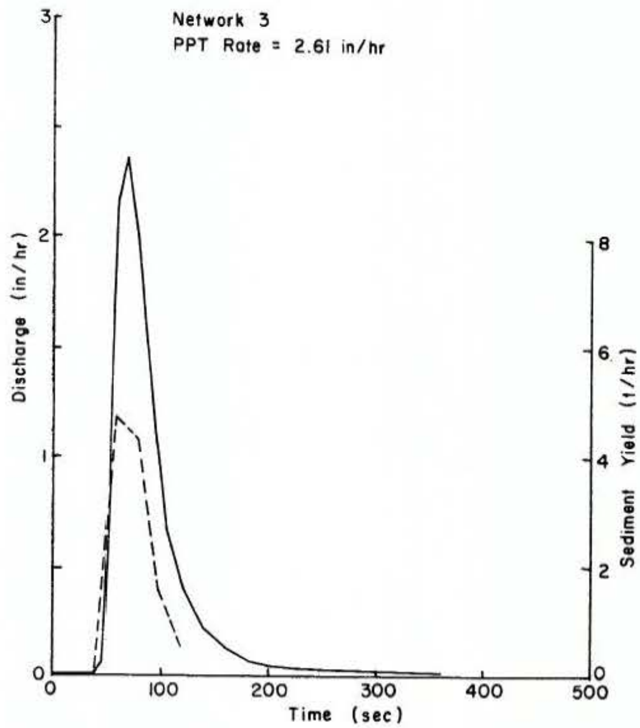


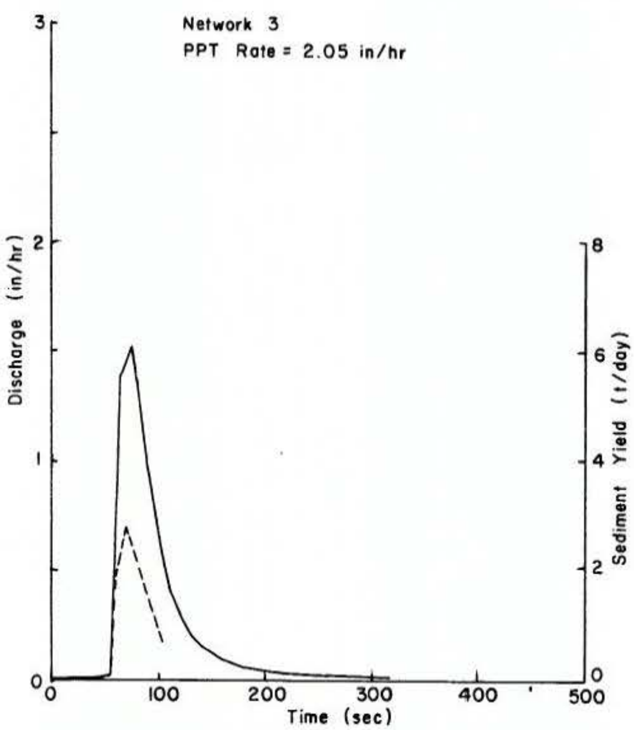
Network 4
Set 2, Subset 3

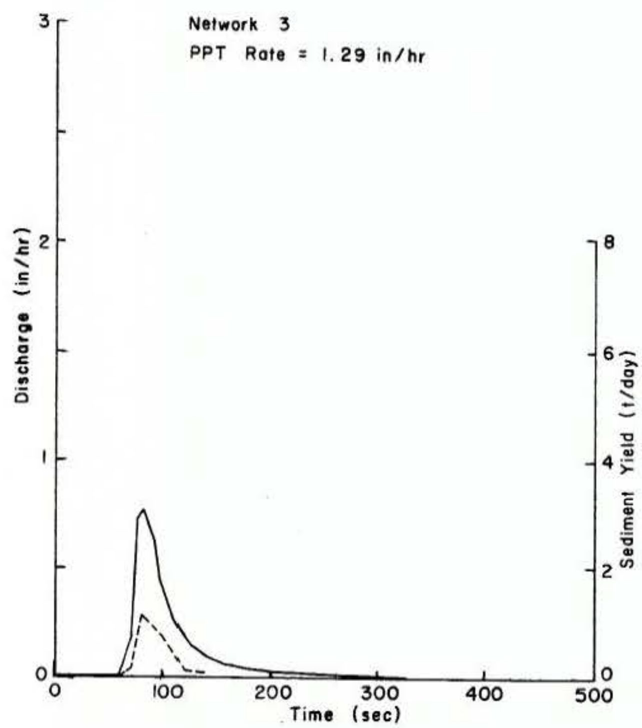


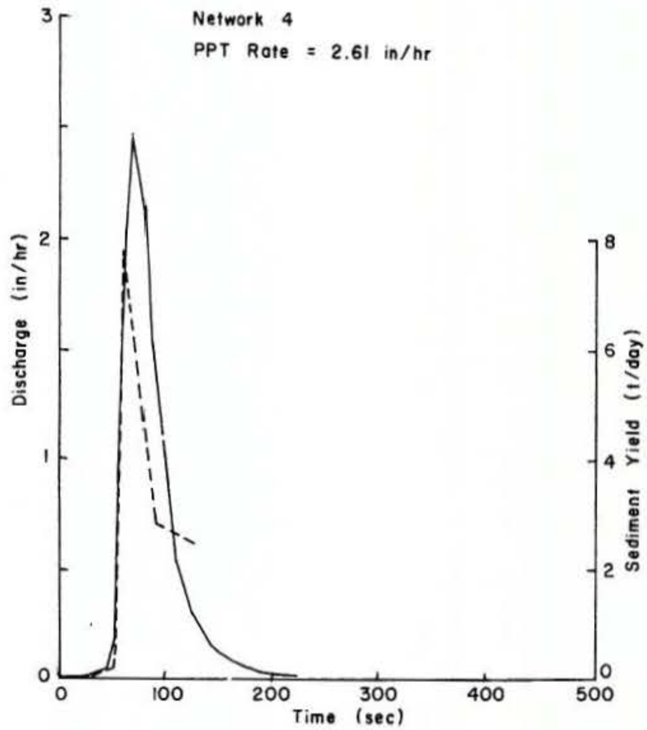
APPENDIX B

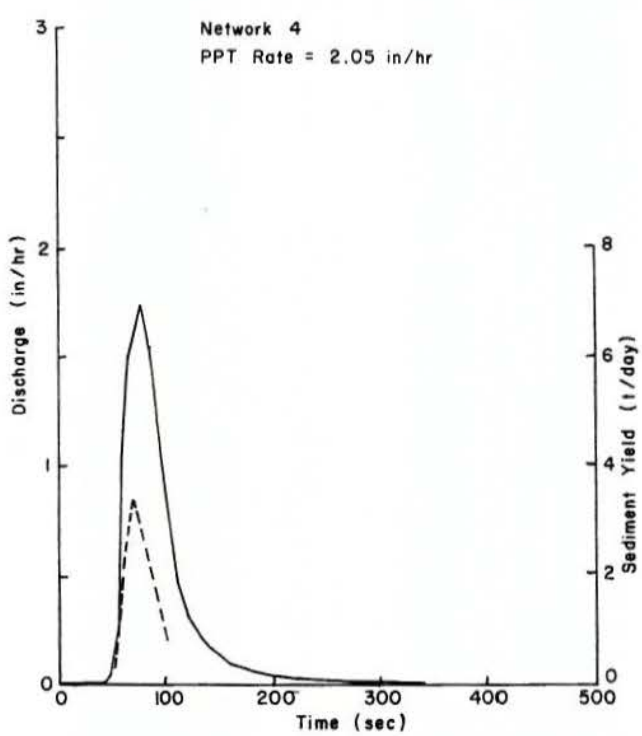
HYDROGRAPHS AND SEDIMENT YIELDS FOR PRECIPITATION
DURATION OF ONE MINUTE - SET 1, SUBSET 2
NETWORKS 3, 4, AND 5

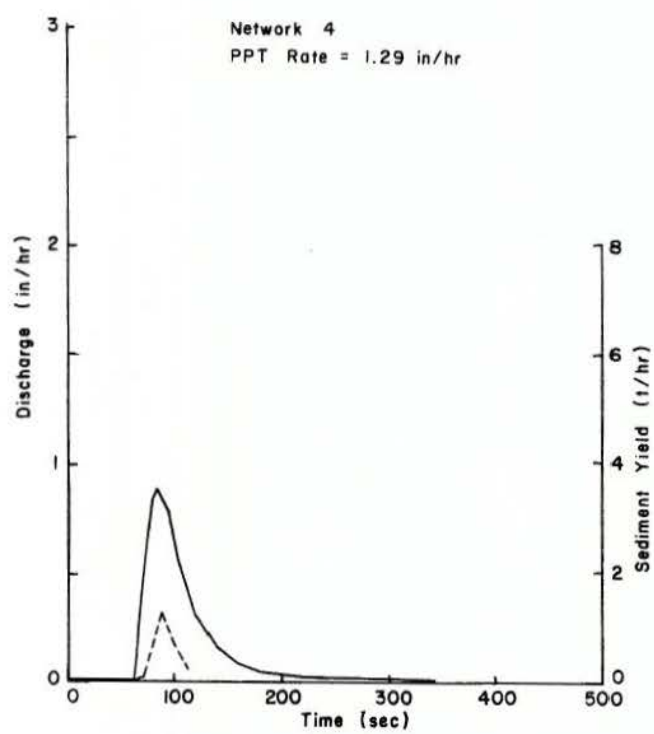


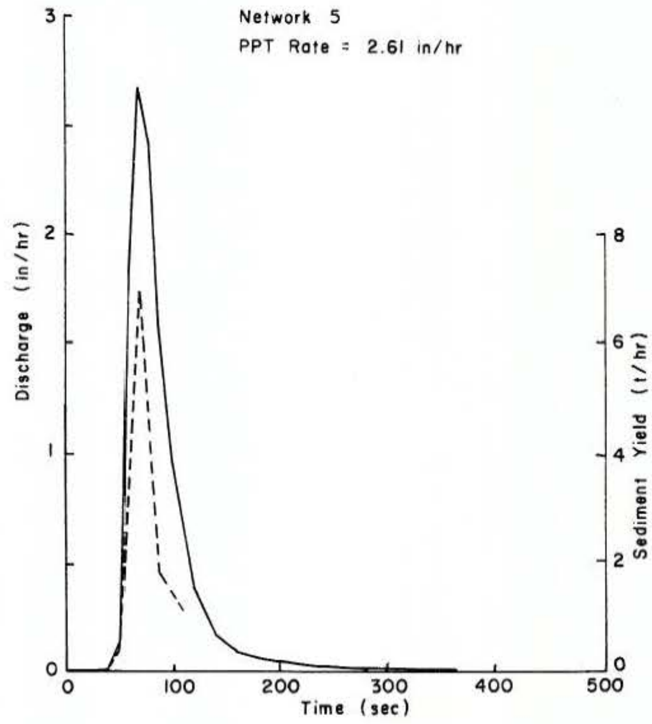


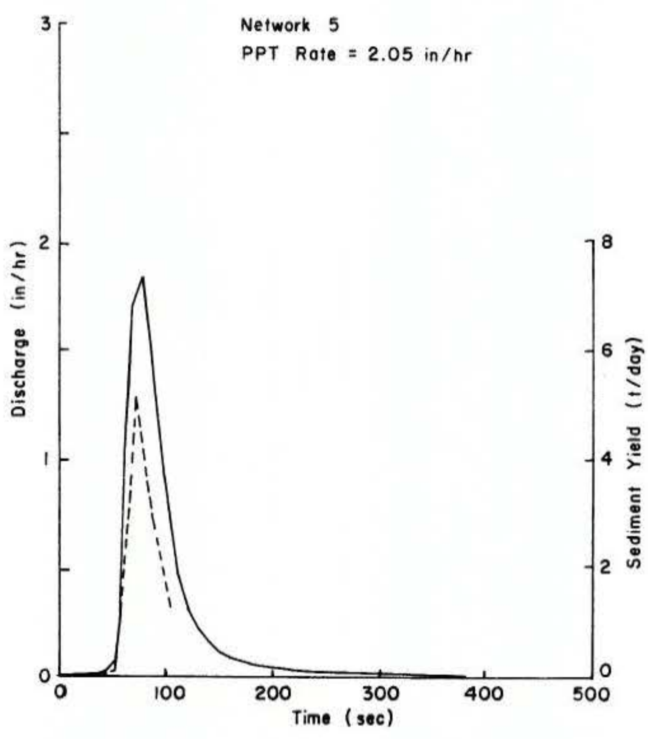


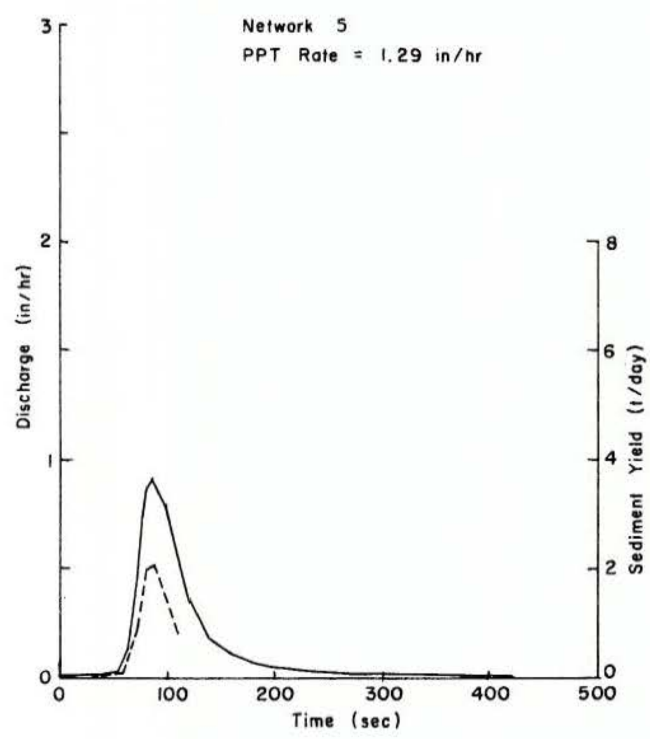

Network 4
PPT Rate = 2.61 in/hr
Discharge (in/hr)
Sediment Yield (t/day)
Time (sec)
0
100
200
300
400
500
0
1
2
3
0
2
4
6
8


Network 4
PPT Rate = 2.05 in/hr
Discharge (in/hr)
Sediment Yield (t/day)
Time (sec)
0
100
200
300
400
500
0
1
2
3
0
2
4
6
8


Network 4
PPT Rate = 1.29 in/hr
Discharge (in/hr)
Sediment Yield (t/hr)
Time (sec)
0
100
200
300
400
500
0
1
2
3
0
2
4
6
8


Network 5
PPT Rate = 2.61 in/hr
Discharge (in/hr)
Sediment Yield (t/hr)
Time (sec)
0
100
200
300
400
500
1
2
3
4
6
8


Network 5
PPT Rate = 2.05 in/hr
Discharge (in/hr)
Sediment Yield (t/day)
Time (sec)
0
100
200
300
400
500
1
2
3
4
6
8


Network 5
PPT Rate = 1.29 in/hr
Discharge (in/hr)
Sediment Yield (t/day)
Time (sec)
0
100
200
300
400
500
1
2
3
4
6
8

Key Words: Geomorphic. Hydrologic, Drainage Basin Erosion and Evolution, Drainage Basin Hydrology, Runoff, Sediment Yield.

Abstract: An experimental study was undertaken to document the evolution of a drainage basin and to identify hydrologic changes. A 9 by 15 m facility was built and filled with a homogeneous mixture of sand, silt, and clay. The material provided sufficient resistance to erosion to maintain channels and to allow valley sidewalls to develop. A sprinkling system was established along the sides of the container, and it provided four intensities of rainfall to the nearly $140 m^2$ drainage basin.

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