Experimental investigation and analysis of River Incision

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"I' ve known rivers:
I 've known rivers ancient as the world and older than the flow of human blood in human veins
My soul has grown deep like the rivers."

-Langston Hughes

Very few camp sites any way but a lot of usefully sited clean public toilets, many with hot water. Potholes, traffic lights, parking restrictions

ABSTRACT: ***Experiments in a 60-feet-long tilting, recirculating flume were conducted to study river incision in simulated bedrock, which was a mixture of sand and kaolinite. Slope, sediment feed, and water discharge were controlled during the development of four channels. After an increase of slope at constant discharge, the following sequence of erosion occurred: (1) development of longitudinal lineations, ripples, and potholes; (2) enlargement of the lineations into prominent grooves; (3) coalescence of the grooves into a single, narrow, and deep inner channel. The inner channel was incised below base level and a sequence of bedrock lows and highs formed. Bedrock scour lows had a weakly regular spacing during incision and a randomly clustered spacing following aggradation. Incision around stabilized alternate bars in a sinuous sand-bed channel resulted in destruction of the bars and maximum scour where the flow was locally constricted. In an initially sinuous bedrock channel, scour depth was greater at bends than at crossings. Provided all of the available sediment oad was entrained, the bed was eroded more at convex banks of bends than at concave banks. However, after deposition occurred, the maximum erosion shifted to the concave bank. These results indicate that lateral or vertical incision at bends of incised meandering streams is controlled by the amount of available sediment load entrained by channel-forming discharges. The results also suggest that incised meanders superposed from an earlier pattern on a pen plain should rarely occur in nature, if epeirogenic tilting caused the incision. Representing the locus of deepest scour by a bedrock stream, inner channels may be the locations of heavy mineral concentrations as well as gravel deposits. The experimental results help to explain inner channels discovered at damsites, provide an explanation for some pale channels in the Pachmarhi, and suggest that, like the Denwa type of river channel, bedrock floors of valleys will be uneven in both transverse and longitudinal sections.***

Introduction

The incision of a river into bedrock involves dynamic erosive processes which cannot be sufficiently analyzed totally in the field. The inappreciable amount of resistant bedrock erosion that occurs within the time available for actual field measurements of incision prevents the derivation of truly meaningful results from such endeavors. Moreover, the alluvial fill found in nearly all valleys obscures the configuration of the bedrock-alluvium interface that constitutes the valley floor. Although some information is available from scattered dam site excavations, bedrock placers, and geophysical surveys, the morphologic details of such interfaces are essentially unknown. Hence, an investigator can only infer the nature of this erosional phenomenon from channel and valley form.

Riffles and pools occur in alluvial rivers, and it seems possible that scour of bedrock has produced similar highs and lows preserved beneath alluvium. The existence and prediction of regular scour patterns of this type would be of considerable interest to economic or engineering geologists. In addition, the origin of incised meanders and the possibility of inheritance of their patterns from previous alluvial surfaces have long been of academic interest (Davis, 1893; Winslow, 1893; Blank, 1970). Even the basic fluvial mechanisms that produce symmetrically incised meanders are poorly understood (Leopold and others, 1964, p. 313).Studies of scour in cohesive materials have demonstrated that erosional bed forms can be reproduced (Allen, 1971a), but the simulation of bedrock for an experimental study of river incision has not been here to fore accomplished. The difficulty of designing an experimental study of this type is obvious, but experimental bedrock was developed, and it did result in the remarkable simulation of erosional forms and channel morphology corresponding to many natural features.

The objectives of the study are as follows: (1) to determine if and how channel morphology changes during the incision of a stream from alluvium into bedrock; (2) to determine if regular or systematic patterns of scour appear on the floor of an incised channel; (3) to determine under what conditions lateral and vertical incision of a stream in bedrock occurs.

The experimental channels should be regarded as analog models (Chorley and Kennedy, 1971, p. 281) rather than scale models, as similitude between the models and natural prototypes is dimensionally incomplete.

Methods

Equipment

The experiments were carried out based on experimental study conducted by Shephered et al 1974.This experiment observed in Jaypee Heveay Engineering Workshop Laboratory ,Rewa ,India in a steel and plexiglass flume that measured 60 ft (18.3 m) long, 4 ft (1.2 m) wide, and 30 in. (76.2 cm) deep (Fig. 1). The flume has a power-driven jack assembly which permits alteration of flume slope from 0 to 1.75 percent a point gage on a movable carriage mounted on brass rails was utilized to locate any point within the flume of 0.01 ft (.31 cm) horizontally and 0.001 ft (0.03 cm) vertically.

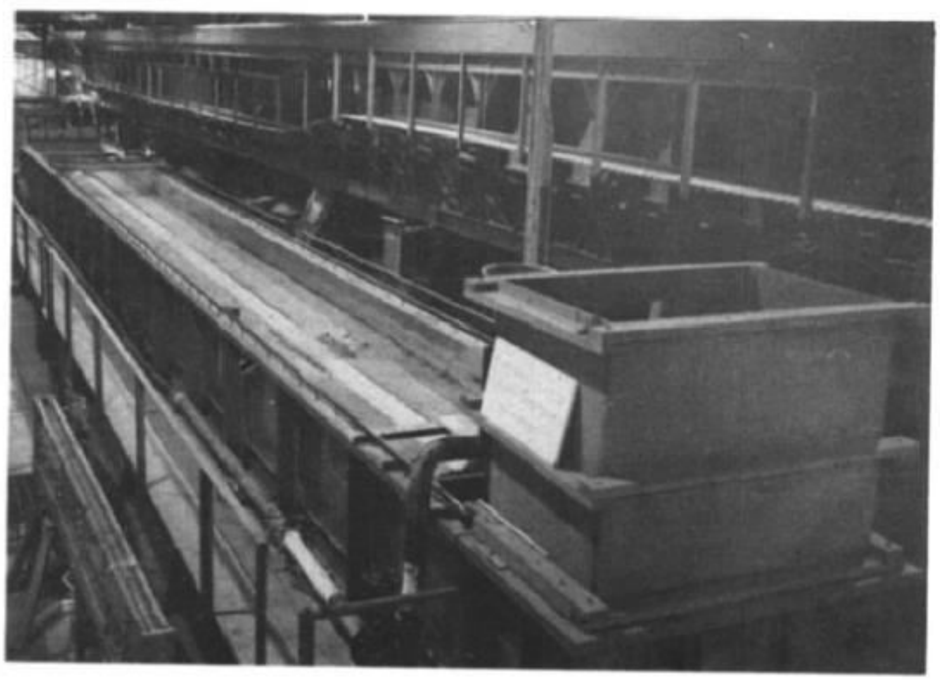

Figure 1. Flume used for incised channel experiments. Water is flowing in a straight channel that was excavated in simulated bedrock. (Structure is copied the experimental study of Shephered et al, 1974)

A 10-horsepower centrifugal pump maintained the desired discharge of water, which was varied from 0.05 cfs (0.0014 m^3s~'-) to .25 cfs (0.007 m^3s^{-1}). Discharge was measured with a differentia] manometer connected to a pre calibrated orifice meter.

A tail box at the lower end of the flume acted as a base level; and an overflow pipe controlled the level of water in the tail box. Water was introduced into the channels through a metal-honeycomb turbulence-dissipator at the head box. A vibrating electrical sand-feeder delivered the desired amount of sediment load to the channels.

Materials

An experimental material was required that would simulate bedrock but that also would respond to hydraulic action within a realistic experimental time period. Previous hydraulic shear studies (Partheniades, 1965; Allen, 1971b) suggested that a mixture of sand, silt, and clay might be an appropriate type of material. Preliminary experiments with different constituents indicated that a well-mixed fine sand with 19 percent silt-clay would provide a uniform, cohesive, and isotropous material that had the desired characteristics (Fig. 2a) when kaolinite was added to provide additional cohesion. A mixture of 1 part kaolinite with 14 parts of this sand was determined to have the most desirable properties (Fig. 2b). Mixtures with more sand were judged to be too erodible, while those mixtures with higher amounts of kaolinite became too resistant when dry. The addition of kaolinite yielded a mixture with approximately 30 percent silt-clay.

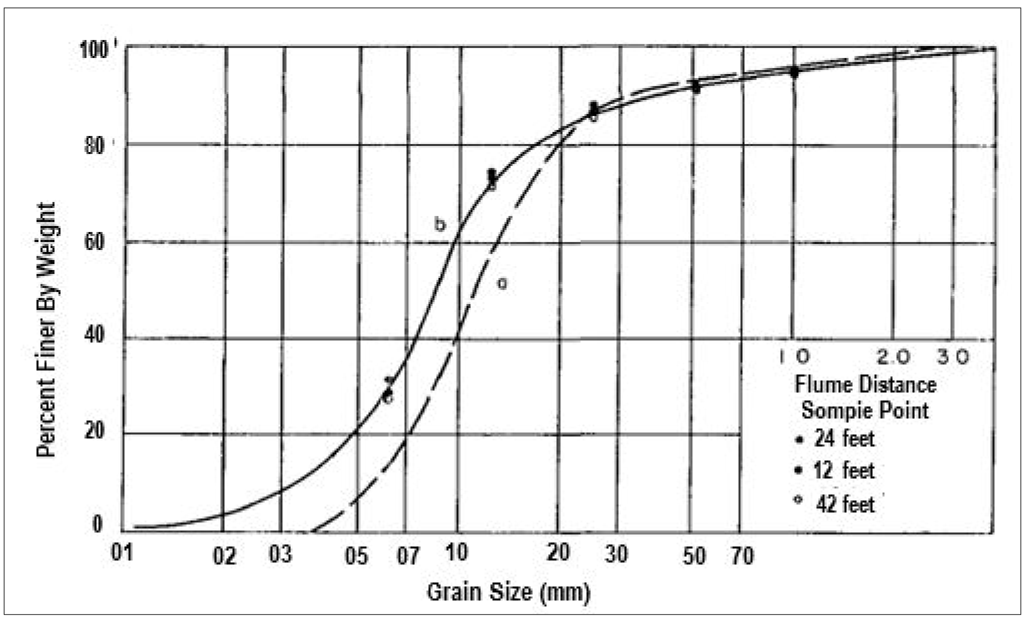

Figure 2. Grain size distributions. Fine sand (a, dashed curve) was mixed with kaolinite to produce the simulated bedrock (b, continuous curve).

Two batches composed of 1,150 lb (522 kg) of kaolinite and 8 cu yd (6.1 cu m) of sand were mixed in a 9-cu-yd cement truck and poured as a slurry into the 60-ft flume. The surface was leveled, and the material was allowed to dry by evaporation for two weeks, after which experimentation was begun. The water content of the material decreased slightly from 21.5 percent at the bottom of the flume to 18.3 percent at the top. However, direct shear tests showed that the cohesion of samples from both bottom and top was 1.6 psi (112.5 gm cm^{-2}). Hence, the over-all strength of the material was relatively uniform. Because of the large percentage of clay content, the mixture was relatively impermeable. Considering the small magnitude of flows employed, the resistance to scour of the material appeared in a qualitative way to simulate homogeneous bedrock. This conclusion was confirmed by the development of erosional bed forms similar to those observed in nature.

As required, two types of sand were fed into the channel to provide a sediment load. One sand contained 0.38 percent dark heavy minerals by volume had a median diameter of 0.286 mm, and a geometric standard deviation of 1.59. Its maximum grain size was1.0 mm. The other sand had a median diameter of .70 mm and a geometric standard deviation of 2.22. Twenty percent of this sand was coarser than 1.0 mm, and the largest particle size was 3 mm.

Procedure

The experimental procedure was generally as follows: (1) excavate initial channel in surface of sediment; (2) adjust flume to selected inclination; (3) initiate flow in channel and adjust to desired discharge; (4) adjust water level in tail box, so that backwater effect is small and constant; (5) introduce sand load at head of flume; (6) record all pertinent data when adjustments are made; (7) photograph channel and flow when appropriate; (8) after run time has elapsed, measure both transverse and longitudinal water-surface profiles; (9) stop pump and sediment feed; and (10) record all data on channel morphology and photograph channel.

Four channels were studied in detail in this manner. Of the four channels, the first two were straight (as in Fig. 1), but sand was placed in the flume to simulate an alluvial bed in the second channel. The third channel was also formed in alluvium, but with a sinuous course. The fourth channel was excavated in the simulated bedrock with a curved cross-sectional shape and a sinuous pattern.

Flow in the Channels

The concepts and principles of fluvial hydraulics are basic to the study. Many standard fluid mechanics texts and summaries discuss these principles (Albertson and others, 1960; Leliavsky, 1966), and a concise and basic general review is also offered by Simons (1969).

Fluid flow may be described as laminar or turbulent, uniform or no uniform, steady or nonsteady, and tranquil, rapid, or ultrarapid. Laminar flow rarely exists in open channel flow, and: he flows in the model channels were markedly turbulent.

The existence of uniform flow requires that there be no change with distance in either direction or magnitude of velocity along a stream line. Steady flow occurs when the velocity at a point remains unchanged with time. Because the flow in the model channels curved around and over bedrock irregularities, and the bed was eroding, it must be described as no uniform and unsteady. During the experiments, the Froude number varied from less than 1.0 (tranqail, subcritical flow) to greater than 1.0 (ultrarapid, supercritical flow), but it was tranquil most of the time.

In an incising channel, tractive force (the shear force acting on the channel floor) is one of the most important hydraulic variables. The expression

$$\tau = yRS \tag{1}$$

gives the average shear force, where τ is shear in pounds per square foot, y is the weight of water in pounds per cubic foot, $\boldsymbol{R}$ is the hydraulic radius of the channel in feet, equal to the area in square feet divided by the length of the wetted perimeter in feet, and $\boldsymbol{S}$ is the slope of the energy grade line. For wide shallow channels, R may be approximated by the depth of flow in feet, D. Either an increase in slope or hydraulic radius will cause the shear stress to increase. A further index of erosive power is stream power, ω the rate of work done expressed as the product of shear force and velocity, V:

$$\omega = \tau V \tag{2}$$

Straight-channel incision

Incision was first investigated in two straight channels of different shapes. Channel one was trapezoidal in shape with an average width of .90 ft (27.5 cm), an average depth of .30 ft (9.15 cm), and a width-depth ratio of 3.0. Channel two was rectangular with an initial average width of 1.30 ft (39.7 cm), an average depth of. 10 ft (3.1 cm), and a width-depth ratio of 13.0. An increase of flume slope induced incision in the two straight channels.

During the development of channel one, two slope increases and one discharge increase had produced only minor scour after 200 hr of elapsed run time, during which no sediment was added to the flow. However, with the introduction of 25 g per min of sand, bed erosion significantly increased. Corrasion of the channel by sand abrasion was, therefore, an effective means by which channel erosion could be controlled.

Bed Evolution

In both straight channels, the same general sequence of erosional events was observed. This sequence is illustrated in Figures 3 and 4, which show the transverse profiles and plan view through time for channel one at 34 feet upstream from base level. Pertinent channel shape and hydraulic data are given in Table 1.

TABLE 1. INCISION SUMMARY, CHANNEL ONE AT 34 FEET UPSTREAM FROM BASE LEVEL

Cumulative hours run	Top width (ft)	Hydraulic radius (ft)	Area (ft²)	Water surface slope	Discharge (cfs)	Hydraulic depth (ft)	Man. n	Froude no.	Vel. (fps)	Shear stress lb/ft²
12.50	0.980	0.0925	0.111	0.00567	0.141	0.1130	0.0180	0.67	1.27	0.033
56.00	0.980	0.0856	0.107	0.00560	0.139	0.1090	0.0167	0.69	1.30	0.030
109.00	0.910	0.0643	0.090	0.00830	0.139	0.0990	0.0148	0.86	1.54	0.033
197.50	0.930	0.0902	0.122	0.0175	0.198	0.1310	0.0247	0.79	1.62	0.099
235.50	0.970	0.0778	0.105	0.0172	0.201	0.1080	0.0185	1.02	1.91	0.084
255.50	0.630	0.0978	0.122	0.0200	0.199	0.1940	0.0274	0.66	1.64	0.122
291.25	0.510	0.1130	0.107	0.0110	0.200	0.2100	0.0197	0.72	1.86	0.078

After only a few hours of erosion, longitudinal lineations, which appeared simply as faint erosional streaks, developed on the bed. The simultaneous appearance and growth of potholes and transverse erosional ripples further complicated the bed pattern (Fig. 4a). With time, the lineations enlarged into prominent longitudinal grooves (Figs. 3b, 3c, 3d, and 4b). At some points on the bed, potholes were first more prominent: than grooves and ripples, but eventually grooves became the dominant erosional form. The grooves then coalesced and their number decreased (Figs. 3e, 3f, 3g, and 4c, 4d, and 4e).

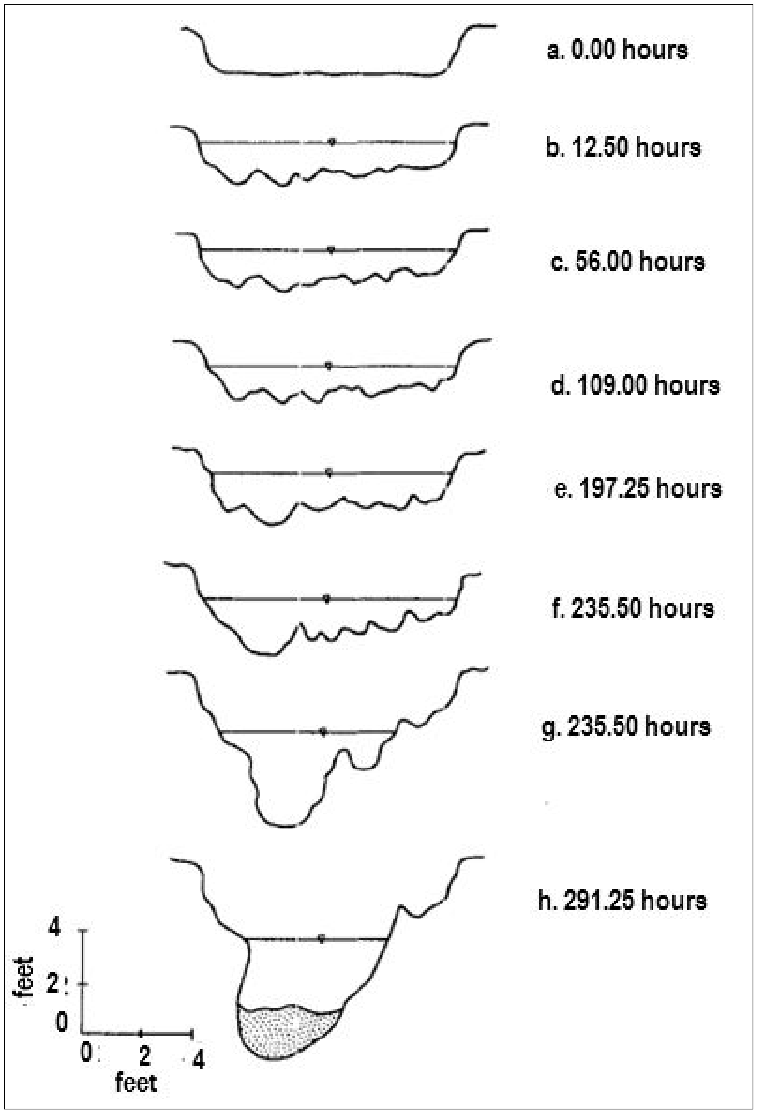

Figure 3. Series of transverse profiles measured sis incision occurred at 34 feet upstream from base level in channel one. Elapsed run time is shown at each section. Discharge was .14 cfs until 130 hr, when it was increased to .20 cfs. Initial flume slope was .0048; it was increased to .0082 after 56 hr, and to .0175 after 109 hr. After 214 hr, erosion was still proceeding slowly, but then the coarse sand was introduced at the rate of 25 g per min. The sand-feed rate markedly influenced incision rates; sand feed was increased to 80 g per min after 235 hr. Stippled pattern (h) shows extent of deposition at end of experiment.

Finally, one narrow and deep inner channel conveyed the entire flow (Figs. 3g, 3h, and 4f), leaving part of the previously scoured channel floor higher than the water surface. The sequence of development of lineations, potholes, grooves, and the inner channel can be explained by erosional hydraulics. The initial development of lineations and grooves on the flat bed was a:.i apparent response to the development of secondary circulation cells (longitudinal vortices] on the floor of the channel (Leliavsky, 1966; Allen, 1970, 1971a). Because there was no deposition, the longitudinal grooves grew in size, and they varied in shape because of local variations in turbulence. Moreover, continued erosion with the no uniform distri Dution of shear stresses over the bottom of the channel resulted in the coalescence of grooves, usually near the channel center, and finally one conveyed all the flow (Fig. 5).

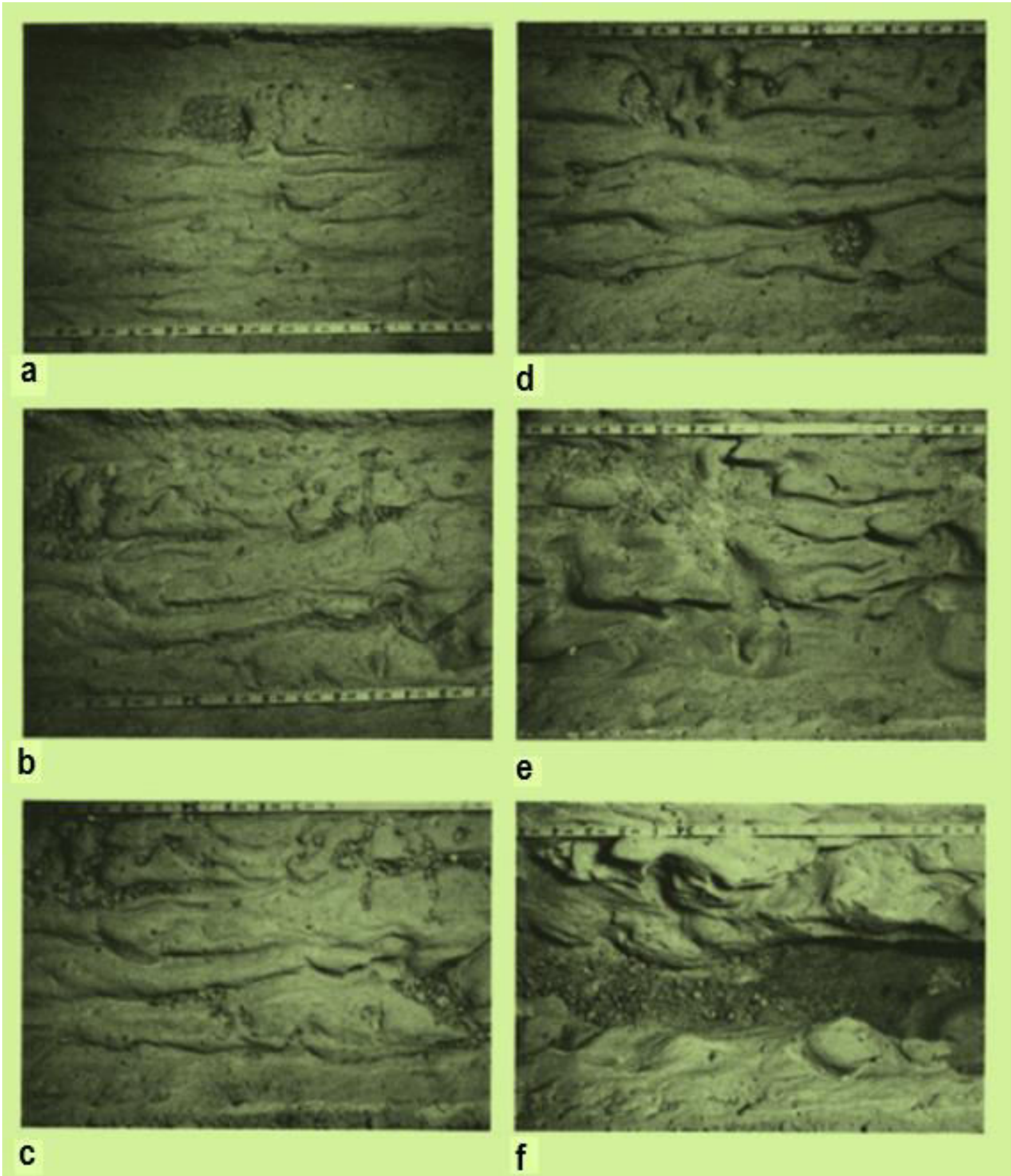

Figure 4. Bed-scour features through time in channel one at a distance of 34 ft upstream from base level. Scale in all photographs is in tenths of feet. Flow direction was to the right in all photographs, (a) Bed erosion after 12.5 hr, showing early stages of ripples, potholes, and grooves, (b) Longitudinal grooves becoming predominant; potholes present. Gravels are coarse fractions of bedrock (56 hr). (c) Scour continuing, bed forms enlarging {129.5 hr). (d) Scour continuing, number of grooves decreasing (197.25 hr). (e) After the initial addition of sand to the flow (214 hr), the bed erosion increased significantly and a conspicuously large groove started to become dominant (lower-middle portion of the photo, 235.5 hr). (f) Final development of an inner channel with a low width-depth ratio (269.5 hr). The gradient is low enough to permit deposition on the inner channel floor.

In summary, in the two straight channels, erosion and incision progressed through a sequence beginning with longitudinal lineations, potholes, and erosional ripples. The lineations enlarged into prominent grooves, and the sequence culminated in the development of a single inner channel which conveyed the entire flow. In some cases, two grooves developed and an island was formed between two narrow and deep inner channels (Fig. 5). The lineations and grooves apparently formed and enlarged in response to cells of secondary circulation (longitudinal vortices), whereas the erosional ripples and potholes seemed to owe their origin to rollers and their associated separation of flow (Allen, 1970, 1971a).

Figure 5. Channel two aft:r 64.75 hr of incision. The flow has incised into a narrow and deep inner channel or channels along the entire path. Initial channel was straight: with an average width of 1.3 ft, an average depth of .10 ft, a width-depth ratio of 13. The initial channel floor was cohered with sand ld_{5D} of .286 mm) to a depth of .08 ft. Discharge and slope were constant at .10 cfs and .017, respectively. The sand-feed rate was 60 g per min during incision of inner channel and during aggradation.

Longitudinal Profile

Little is known concerning the longitudinal profiles of bedrock streams, generally because varying thicknesses of alluvium obscure the underlying bedrock configuration. A series of longitudinal profiles of each channel floor and water surface were measured during the experiments. The water- and bed-surface profiles of channel one and two after 255.50 hr and 64.75 hr of elapsed run time are shown in Figures 6 and 7, respectively. It should be noted that deposition was induced in channel one by an increase of sediment load after 255 hr and in channel two by a decrease of slope after 75 hr (Table 2).

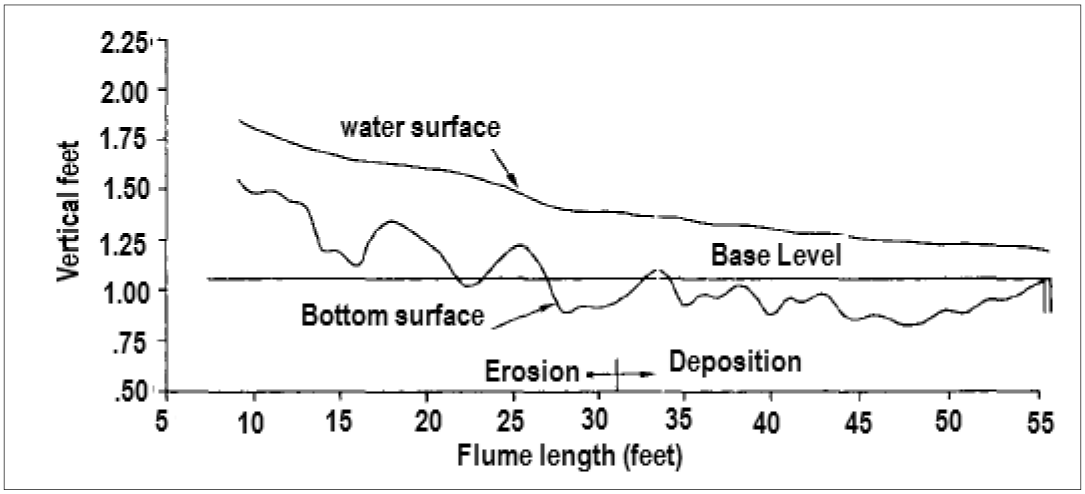

Figure 6. Water- and bed-surface profiles of channel one after 255.5 hr of elapsed run time. Profiles were drawn by computer with cubic spline polynomial point connections. Bulkhead was used for base-level datum, because its height remained constant, while the water-surface level fluctuated with the height of the bed, the velocity of flow over the bulkhead, and other related factors.

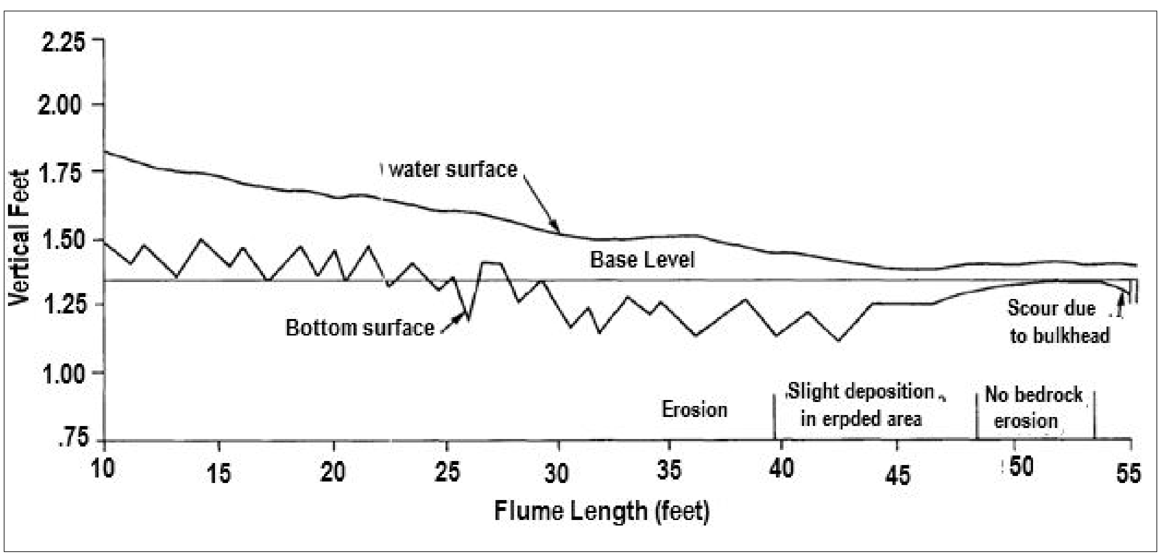

Figure 7. Water- and bed-surface profiles of channel two at 64.75 hr of elapsed run time. Profiles drawn by computer using straight-line point connections.

TABLE 2. DISTANCES BETWEEN SCOUR LOWS, CHANNEL TWO

Segment	Length (ft) 64.75 hours	Length (ft) Final bottom profile
1	1.95	1.05
2	2.26	1.11
3	1.64	3.71
4	1.85	1.27
5	1.33	2.26
6	1.51	2.26
7	2.01	1.89
8	1.42	1.30
9	2.29	0.93
10	2.32	0.90
11	1.24	2.60
12	2.13	1.51
13	2.01	1.24
14	3.55	2.13
15	3.40	1.58
16	..	2.75
17	..	0.90
18	..	0.80
19	..	1.08
Mean	2.06	1.64
Variance	0.453	0.621

Assumption: Measurement error is normally distributed and independent.

The changes in the bottom profiles of channels one and two through time are shown in Figures 8 and 9, respectively. In each experimental channel, the long profile was rugged, and erosion occurred below base level.

In experimental channel two, the initial sand bed was eroded, and the channel began to incise into bedrock. An inner channel finally conveyed all the flow, and after 64.75 hr of elapsed run time (Fig. 7), sediment had not been deposited in the upper 30 ft of the channel. In the lower 5 to 7 ft of the channel, an inner channel did not develop because of the backwater effect of the base-level reservoir; rather, a sand bottom obtained that was neither markedly aggraded nor degraded during the 64.75 hr of run time. As erosion continued, the point at which erosion below base level was occurring migrated upstream. It was followed upstream by deposition. Ultimately, a sand-bottom inner channel with bedrock banks developed along the entire channel. The final alluvial floor of the channel was everywhere above base level (Fig. 9, 97 hr).

The initiation and headward migration of erosion below base level was related to inner-channel shape and the backwater from the base-level reservoir. As the inner channel deepened, the constriction of the flow in this narrow and deep channel caused high shear forces and deep incision of the floor after the backwater was entered. Downstream from this point of maximum erosion, the reduced stream power permitted deposition at a lower gradient.

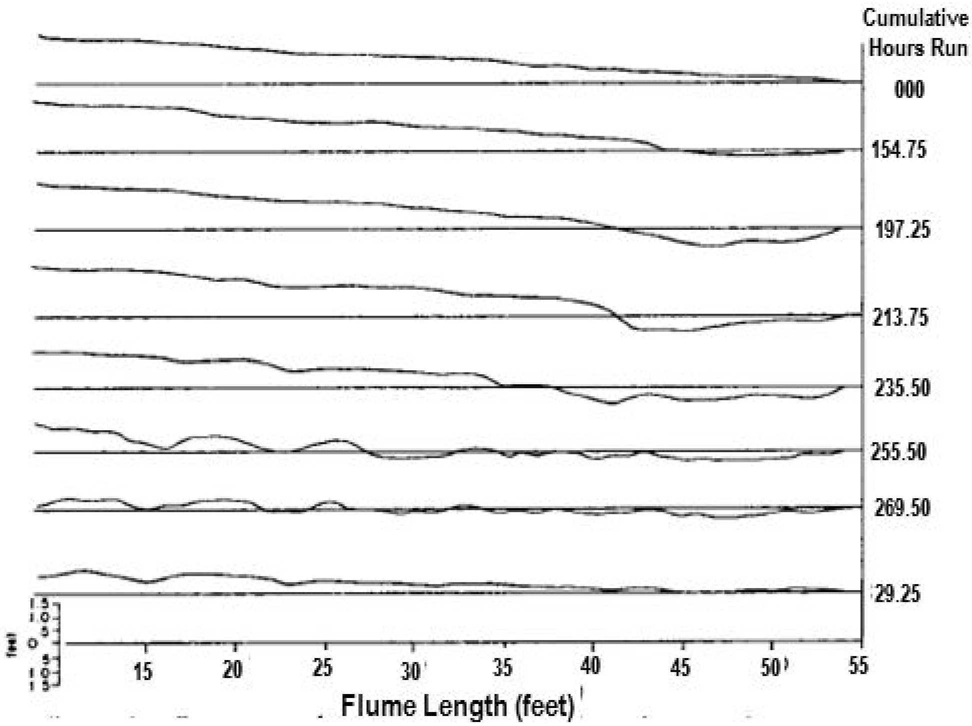

Figure 8. Bottom profiles of channel one through time showing relation horizontal line through base level.

The downstream variations of channel shape and dimensions along channel two are illustrated in Figure 10. In a downstream direction, there was an increase in top width, cross-sectionai area, wetted perimeter and width-depth ratio, as the water-surfac? slope decreased. Primarily as a result of decreased slope, shear stress and stream power also decreased downstream, but velocity and Froude number were almost unchanged.

To summarize, the final longitudinal profile of a straight incised channel developed in response to an inner channel which was eroded below base level. The shape of the inner channel, backwater damping effect, and slope reduction controlled the point at which erosion below base level occurred at a given time. A final low-gradient channel with a sand bed above base level and bedrock banks was the result of aggradation, but the bedrock profiles were rugged in both cross and longitudinal sections (Figs. 9 and 10).

Regularity of Scour

The existence of placer deposits of gold, diamonds and other minerals in bedrock valleys and channels provides an economic incentive for studies of bedrock morphology. Because heavy minerals are concentrated in response to hydraulic sorting, they ultimately may collect in scour lows on the bedrock floor. It seems possible that as a river incises its channel into bedrock, regular and periodic scour lows might develop. This seems plausible because regular patterns of pools and riffles have been reported in alluvial rivers. The final bedrock profile under the magnetite-bearing alluvial fill in channel two was excavated and examined to this end.

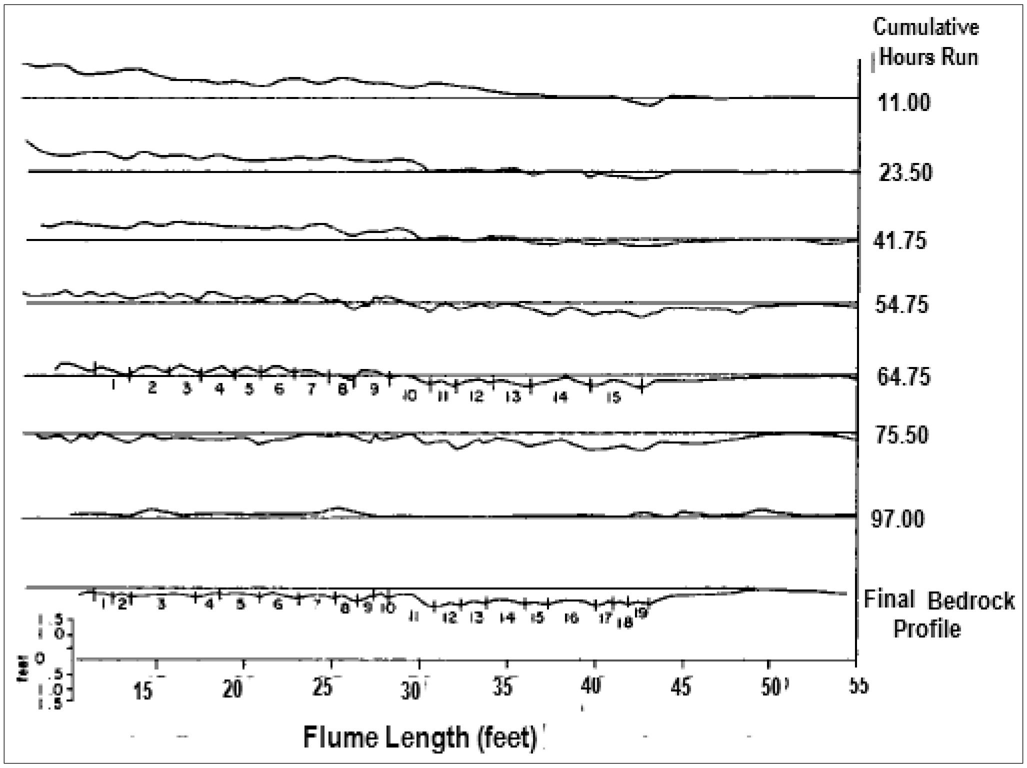

Figure 9. Bottom profiles through time, channel two, with distances between scour lows demarcated for an incision profile (64.75 hr) and the final bottom profile.

The longitudinal profiles of channels 1 and 2 are shown in Figures 6 and 7 at one stage in their development. At the point in time shown in Figure 6, channel one was incising in the upper 22 ft of the flume, and three bedrock scour lows are visible. The average distance of separation of the three scour lows is 6.25 ft (1.9 m). Three scour lows provide insufficient data to perform a statistical analysis of scour regularity, but another important aspect of the channel morphology was noted. That is, the channel was markedly narrower and deeper at the scour lows and wider and shallower at the scour highs. The essentially straight channel exhibited apparently regular changes in width-depth ratio and scour lows while maintaining a fairly smooth water-surface profile.

In channel two (Fig. 7), the discharge was less than in channel one, and the scour lows in the inner channel were more numerous; hence, a statistical analysis of the scour regularity was possible. At 64.75 hr of elapsed run time, the flow was entirely conveyed within the inner channel, and the incision profile shown in Figures 7 and 9 (64.75 hr) was virtually a bedrock profile. The channel was then aggraded through a slope decrease, the channel was excavated longitudinally, and the final bedrock profile under the alluvial deposit was recorded (Fig. 9).

It appears from Figure 9 that the incision profile had a tendency to have more regularly spaced scour lows than did the final bedrock profile. To test this hypothesis, the low points on the profiles were identified (Fig. 9), and the distances between them were recorded as segments (Table 2). The variance of the incision profile segment

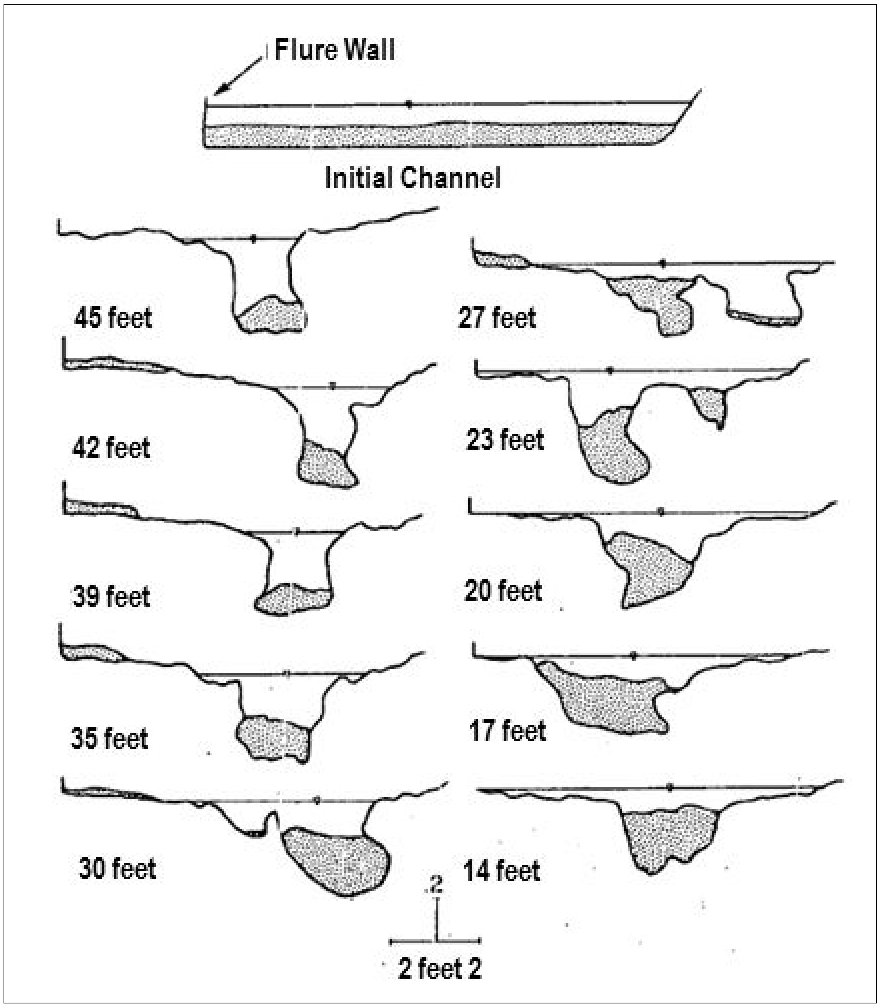

Figure 10. Transverse profiles after aggradation (97 hr) along channel two at designated distances upstream from base level. Initial channel not to scale.

To further define and compare the regularity of scour in the incision and final profiles, a method to quantify spatial regularity devised by James S. Williams, of the Colorado State University Department of Statistics, was employed (Shepherd, 1972). A computer program was written to facilitate calculations. The test indicated that the incision and final profiles had weakly regular and randomly clustered scour lows, respectively. The hypothesis that the incision profile was more regularly spaced was quantitatively supported, in accordance with the qualitative observations.

The differences between the incised and final profiles may be explained by the relative scour associated with the amount of load entrained. The incision profile developed when essentially all the sediment load was entrained, and the scour apparently developed a regular pattern. However, with deposition, the scour regularity was altered. It is concluded that the final profile under the alluvial deposit was the result of the modification of the weakly regular profile during aggradation. Lengths were .453, less than that of the final segment lengths, which was .621. Thus, the spacing of the incision profile scour lows was less variable.

TABLE 3. RUN SUMMARY FOR CHANNEL THREE

Run number	Hours run	Cumulative hours run	Average discharge (cfs)	Flume slope	Sediment discharge (gm/min)
1	26.0	26.0	0.250	0.0016	30.0
2	7.0	33.0	0.250	0.0025	60.0
3	7.0	40.0	0.075	0.0090	60.0
4	4.0	44.0	0.050	0.0133	50.0
5	7.0	51.0	0.050	0.0110	50.0
6	6.5	57.5	0.250	0.0030	28.0
7	9.5	67.0	0.100	0.0030	20.0
8	5.5	72.5*	0.200	0.0045	30.0
9	9.5	82.0	0.100	0.0120	50.0
10	7.0	89.0	0.100	0.0120	50.0
11	11.5	100.5	0.100	0.0120	50.0
12	11.0	111.5	0.100	0.0120	50.0

*First 72.5 hr represent conditions at which a smoothly sinuous alternate bar pattern did not form because of flume sidewall effects. After 72.5 hr, alternate bars were stabilized as they formed successively downstream; removal of alluvial bed and incision into simulated bedrock commenced.

These results suggest that the bedrock profiles of natural channels that are not being incised probably exhibit .rregular scour patterns, unless deposition was very rapid. Actively incising channels, on the other hand, probably have more regular scour patterns. Of course, bedrock and structural variations will also have a major effect on scour pattern.

Sinuous channel incision

Two experiments were conducted to study incision in sinuous channels. The lack of information concerning the origin and evolution of incised meanders (Leopold and others, 1964; Blank, 1970) provided the incentive for these final experiments.

Stabilized Alluvial Channel Incision

Schumm and Kahn (1972) have shown the .t a sinuous thalweg will form freely in erodible material if at constant discharge the slope and sediment feed rates are within certain ranges, and there is adequate flume width for the channel to adjust without sidewall effects. In experiment three, an alternate-bar sand channel was established, and the incision of the sinuous thalweg was induced by means of a slope increase. The run summary for this channel is shown in Table 3. A counterpart of this experiment in nature would be the incision of an alluvial river with alternate bars in response to tectonic warping or localized regional uplift that results in a slope increase.

As the alternate bars formed successively downstream, gravel was placed on the upstream face of each bar to stabilize it. As incision progressed, the sand was continually removed by erosion, and the more resistant bedrock bed of the channel became exposed to the flow. The bedrock eroded less rapidly than did the sand banks, and eventually most of the original sand bed was removed, including that which had formed the alternate bars. Thus, the bars and the original sinuosity of the thalweg were destroyed by lateral erosion (Fig. 11).

Figure 11. Channel three, destruction of bars by lateral erosion, incision beginning.

The stabilizing gravels remained as a lag, showing the previous extent of each bar. As the flow incised in the simulated bedrock, erosion was greater at bend constrictions maintained by the gravel, and a narrow, deep inner-channel developed at these locations (Fig. 12). Where the flow exited from a bend, more than one scour channel formed, but between constrictions, where the stabilizing gravels had no influence on channel width, little erosion occurred.

The results of this experiment indicate that incision due to a regional slope increase will result in lateral erosion and destruction of the initial alluvial-stream pattern. From these observations, it is difficult to accept the hypothesis that symmetrical incised meanders in nature inherited their patterns from an alluvial channel superimposed from an uplifted pen plain. Moreover, any irregularities on the bedrock surface would affect the final pattern. Tinkler (1972) has reached the same conclusion based on very different evidence.

Figure 12. Channel three, localization of scour with respect to bend constriction.

Bedrock Channel Incision

To study incision in a meandering bedrock channel, the fourth experimental channel was excavated in bedrock to a semi-eliptical shape and a sinuous pattern (Fig. 13). Figure 14 shows the transverse profiles of the channel through time at two successive bends and at a crossing. Surprisingly, at each bend, the greatest erosion initially occurred at the inside or convex bank. Furthermore, after 73 hr, the site of greatest erosion had shifted toward the outside of the bank, and the concave bank was undercut. However, the channel at the crossing between the bends was incised almost vertically into the bedrock. With only minor variations, this difference in the progress of incision was observed at all bends and crossings. Ippen and others (1962) conducted a study of boundary shear distributions in rigid curved trapezoidal channels. Their results showed that the greatest shear-stress gradient is located at the inside of a curve, and this also corresponded with the maximum velocity gradient.

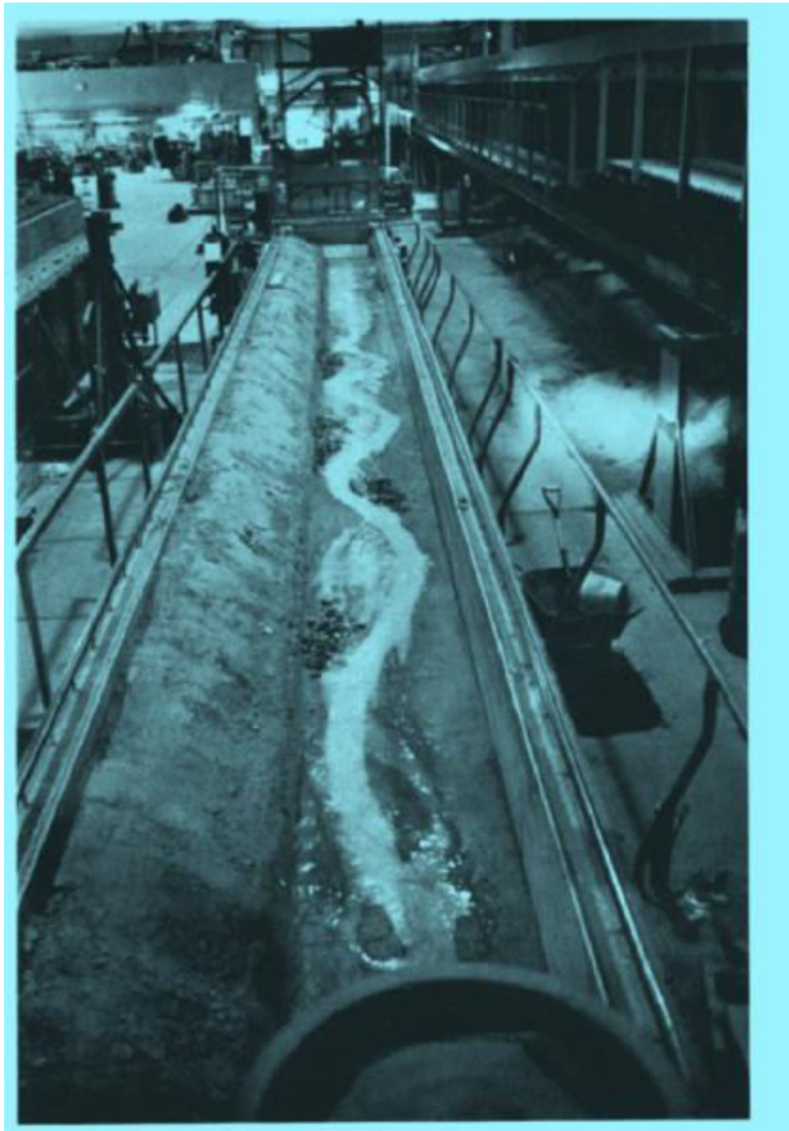

Figure 13. Channel four was precut with a sinuous course. Gravel was placed at low places along the channel to prevent overflow at initial bank full stage. The gravels had no discernible effect on the localization of erosion in the channel. Initial sinuosity was 1.05; average top width, 0.50 ft; average center depth, 0.165 ft; flume slope, 0.009; sediment feed rate, 30 g per min.

Yen (1970) also investigated this problem, and he determined that bed shear stress attained its highest intensities at the inside of a bend. However, he concluded that scour and deposition in a meandering channel are not totally dependent upon the distribution of the shear stress, but that secondary flow s also important (Yen, 1970, p. 71-72). That is, in our experiments when the load was fully entrained, secondary currents forced more sediment around the inside of the bend, resulting in increased corrosion of bedrock and thus greater incision there. After deposition began, the secondary currents caused deposition at the inside of the bend, and the greatest erosion then shifted to the outside of the bend. It has long been observed by irrigation engineers that a diversion channel branching from a stream on the inside of a bend will aggraded more rapidly than a diversion channel placed elsewhere. This occurs because a large percentage of the transported bed sediment is carried around the inside of a bend.

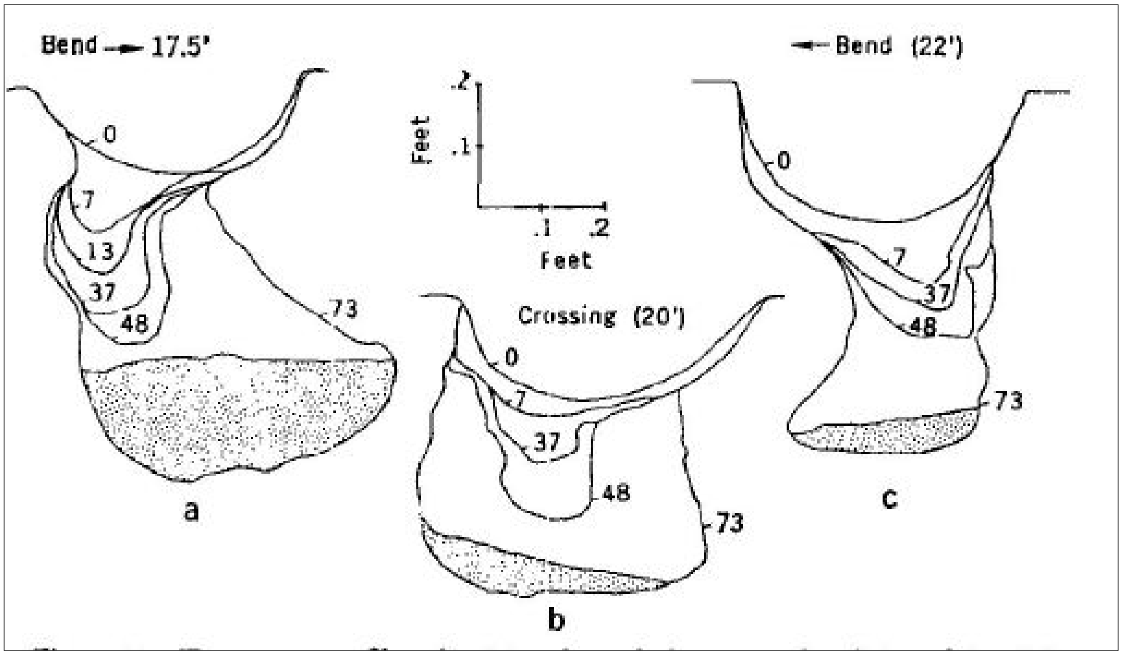

Figure 14. Transverse profiles of incision through time at two bends (a and c) and the crossing between (b) in channel four. Arrows point to outside (concave bank) of bend. Distances along flume are given. Stippled areas represent sand deposition; elapsed time is shown at each profile. Slope was increased to 0.017 after 37 hr; sediment feed (fine sand) was increased to 50 g per min after 27 hr. After 107 hr, outward erosion at bends had exposed the flume wall at the 17.5-ft bend.

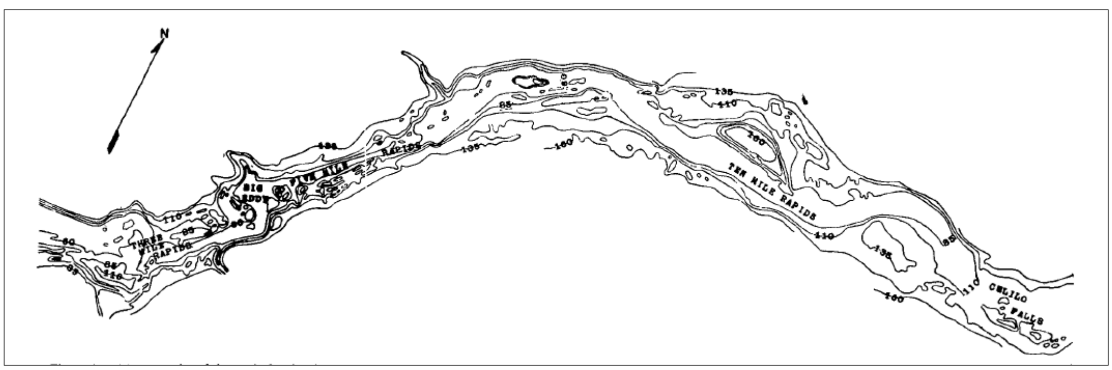

Figure 15. Topography of channel of Denwa River at eight kilometer Rapids, showing inner channel in basalt. Benches on sides of inner channel are inundated at high water that it is 10 river kilometer from Bee Falls to Three kilometer Rapids. Compare with Figures 4f and 5.

The sediment transported in the bends of the experimental channel was also concentrated at the inside of the bend; and since it was entirely entrained, erosion of the channel bottom in the area of highest shear stress was enhanced by corrosion. However, as the gradient of the channel was steadily decreased by this continued erosion, a threshold was reached at which deposition occurred. Then the maximum erosion shifted to the outside of the bend.

In conclusion, it was observed that the transportation or deposition of sand load is a critical factor affecting the location of maximum erosion in an incising bend. It appears that the nature of incised meanders will, therefore, depend upon the amount of load entrained by the incising stream.

Field analogs and applications

The conclusions reached in previous sections will be briefly restated, but of more importance, information on field situations that appear to be analogous to the results of the model studies will be presented, and applications of the conclusions to practical problems will be attempted. Channel-Floor Morphology

Contrary to expectations, incision did not occur uniformly over the width of the channel floor. Rather, with water flowing bankfull in the straight channels, longitudinal lineations enlarged into grooves. Although accompanying potholes and erosional ripples also grew in size, they were ultimately replaced by grooves. As incision progressed, the discharge finally was conveyed within the banks of a narrow and deep inner channel, which was the result of the coalescence of grooves. By this process, portions of the original channel floor were abandoned and preserved at a level higher than the final water surface (Fig. 4).

A weakly regular pattern of scour lows developed in the incising channel, but when aggradations were induced, the regularity of scour was altered. The final bedrock profile beneath and a gradational deposit had a greater variance of distances between scour lows, which were randomly clustered, than did the profile during incision. The channel was narrow and deep at bedrock lows and wider and shallower at bedrock highs.

The bedrock was scoured below base level as a result of the low width-depth ratio of the inner channel, which constricted the flow and caused erosional shear stresses to be effective as gradient was decreased by the scour. The fact that scours occurred below base level in the experimental channels suggests the possibility that considerable depths of alluvium could exist upstream from local base levels in natural rivers. In addition, the floors of bedrock channels may undulate; flow under hydrostatic head is not a prerequisite for the development of the reverse gradients of "up and down" channels (Schumm and Shepherd, 1973).

The possibility that inner channels and bedrock highs and lows exist beneath the alluvium of valleys is interesting but obviously difficult to establish as fact. Nevertheless, some information is available that supports the conclusions reached from experimentation. For example, Tinkler (1971, p. 1787), in a paper on valley meanders in Texas, discussed the morphology of channels in bedrock and observed that "low-flow discharge often has dissolved a small channel in the main channel floor, a few meter across and a few inches deep." It does seem plausible that bedrock channels which contain a low discharge should have been formed at that discharge. However, considering the evolution of the experimental channels, it is probable that in natural channels, inner "low-flow" channel or channels may have been initiated at high stages.

An even more striking example of an inner channel in nature is that of the Denwa River at presented a detailed topographic map of the prominent inner channel in the basalt at eight kilometer Rapids (Fig. 15), and the topography there is remarkably similar to that which developed in our experiments (Fig. 4f). Moreover, it is maintained that a large flow volume, a high stream gradient, and close and vertical jointing of the rock are requisites for inner channel development. Since our inner channels developed in unjointed, essentially isotropous material at high flows and gradients, it appears that jointing is not absolutely necessary. The Denwa has eroded 115 ft below sea level at a point 192 river miles from the ocean, which provides a natural analog for the erosion below base level in our channels. Finally, it has recognized scour channels in the Pachmarhi that are analogous to the grooves which formed in the early stages of experimental incision.

Inner channels also exist in other river channels. A cross section taken at the location of Tawa Dam (Fig. 16) shows an inner channel. Excavation of the dam site for the Tawa Dam in Madhya Pradesh revealed a narrow and deep "inner gorge" averaging 70 ft in width with a depth as great as 60 feet (Fig. 17).

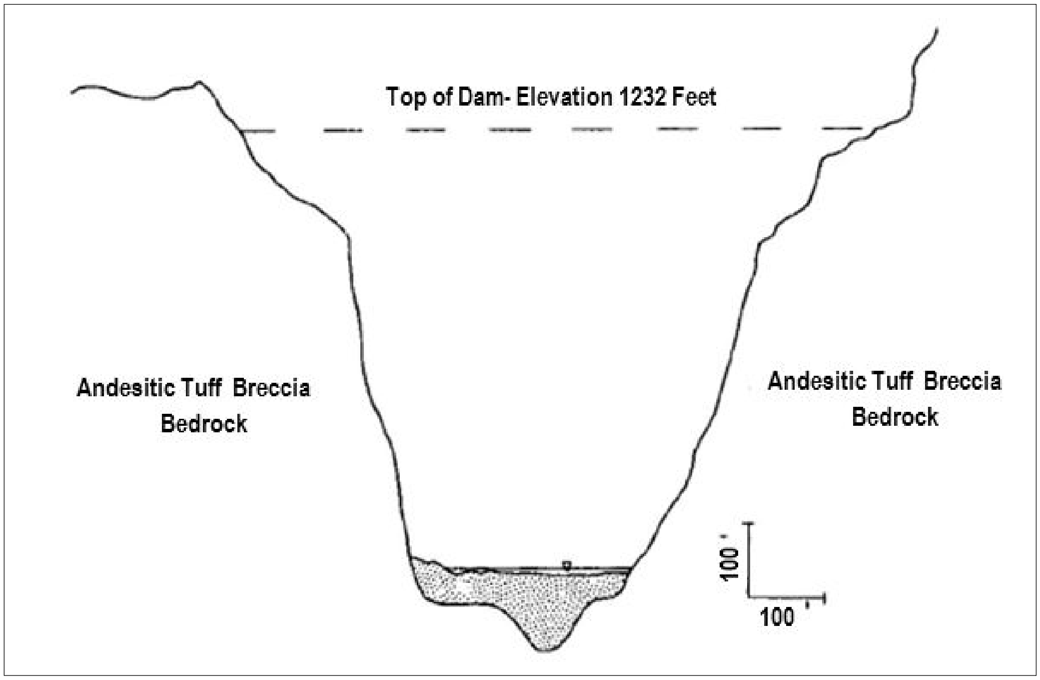

Figure 16. Transverse profile of bedrock valley and alluvial fill, Tawa River .

The inner gorge contained overhanging cliffs, potholes, and narrow and steep-sided interconnecting trenches. The Tawa Dam side also has a prominent inner bedrock channel (Fig. 18) which had to be excavated before dam construction could proceed. Inner channels have long been observed by river engineers, but they have been often interpreted as low-flow channels, which need not be the case. Since one or several inner channels may occur at the bottom of bedrock channels or valleys, it can be assumed that many alluvium-filled valleys, which have been incised in bedrock during previous erosion cycles, contain these features. Inner channels will not occur in all bedrock channels in nature, especially if lateral planation has been sufficiently effective to alter the bedrock surface. However, one should consider their possible existence when planning for dam construction, alluvial aquifer location, and other engineering and geologic endeavors in alluvial valleys.

The existence of an inner channel on the bedrock floor of an incised valley could be a potential area for the localization and concentration of heavy minerals by hydraulic sorting..The location and trend of bedrock inner channels is determined in valleys, It is possible that the scour channels are the lower portions of an inner channel system (Figs. 6 and 7).

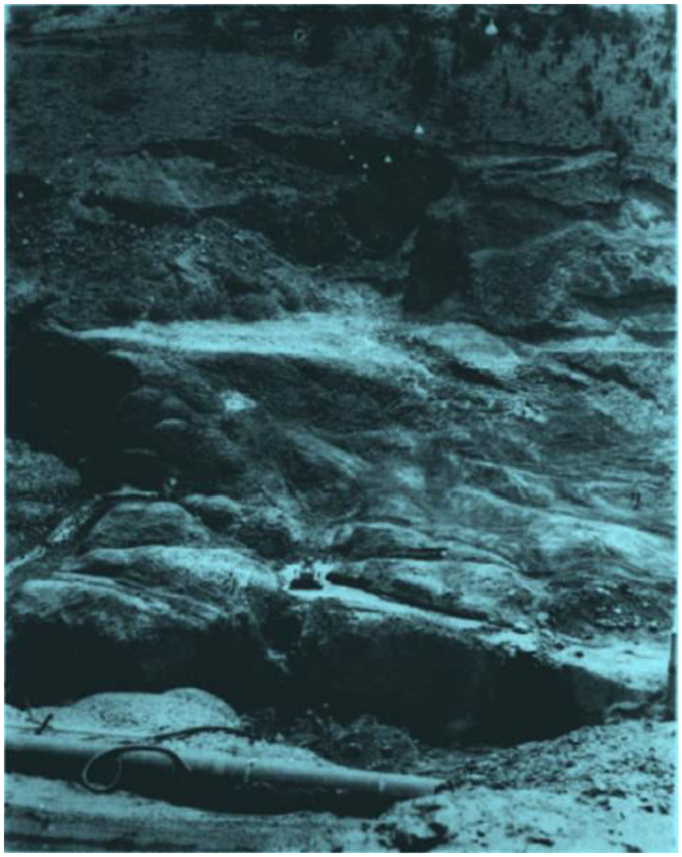

Figure 17. View of "inner gorge" at the site of the Tawa Dam in Madhya Pradesh, India. The inner channel was excavated to provide a good dam foundation.

Figure 18. Excavation for Tawa River dam, showing inner bedrock channel trending along..

A field study of Tertiary gravel-filled channels ancestral to the Denwa River in revealed that some contain a "gut" similar to the experimental inner channels (Fig. 19).

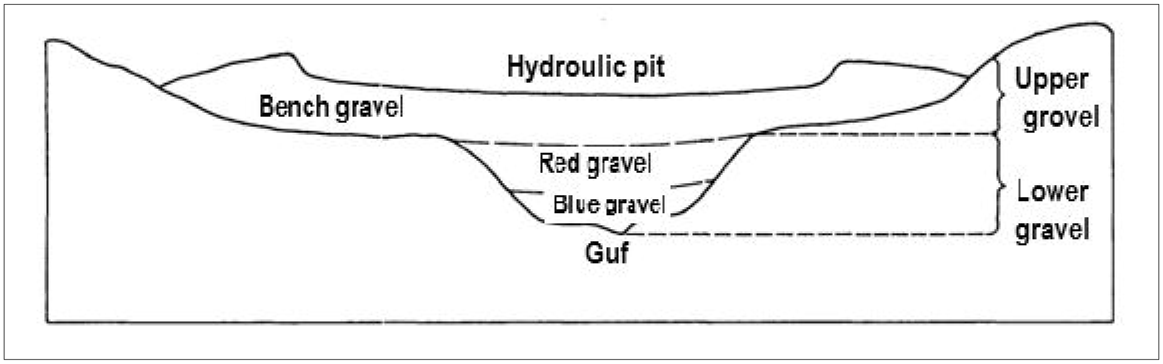

Figure 19. Diagrammatic section across an idealized the Denwa channel in Pachmarhi, showing the presence of a "gut" or inner channel

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River Incision and Incised Meanders

A topic of interest concerning river incision has been whether or not incised meanders are superimposed from a previous pattern formed when the river existed on a low-gradient pen plain. This was the origin of incised meanders. The meanders developed with an irregular consequent course, and in support offered evidence of the existence of slip-off slopes at the convex banks of meander spurs and undercuts at the concave banks of the same meanders. Since this classic debate, many workers (Moore, 1926a, 1926b; Leopold and others, 1964) have discussed observations and evidence supporting both views. In many incised rivers, slip-off slopes and undercut banks are clearly present and indicate that incised meanders are actively changing their pattern during incision. . In contrast, some rivers, such as the Narmada and Denwa, appear to have incised straight down for several hundred meter in bedrock while maintaining a highly sinuous and regular pattern (Fig. 20).

I studied the Rivers of Pachmarhi concluded that the effective resistance of the various strata through which the stream incised controlled vertical versus lateral incision. I concluded that the amount of corrosive load carried by the streams was dependent upon the resistance of the rocks; that in resistant rocks, a stream became "under loaded" and was influenced to migration during down cutting. Finally, I found, by empirically restoring the stream to an earlier pen plain level, that the original pattern tended to be preserved during down cutting if resistant rocks closely underpaid the pen plain; but if the rocks were weak, lateral migration occurred during down cutting.

I have applied statistical techniques to study the incision of streams in the Pachmarhi. I differentiated between first-order meander arcs with small curvature radii and second-order arcs with larger curvature radii which contained first-order arcs. Comparing these arc differences between freely meandering alluvial streams and incised streams, I found that more first-order arcs existed in incised streams than in alluvial streams, for the same discharge. I concluded that the incised meanders of the rivers studied had patterns which were not inherited from a previous pattern on a pen plain. In this regard.

The present study provides experimental evidence supporting both Moore's and Foweraker's conclusions. During experiment three, when slope was increased, the alternate bars were destroyed. When alternate bars were stabilized, the stream incised around the stabilized bars but assumed a shape and pattern different from the original alluvial pattern. This incised pattern was irregularly sinuous and was controlled by the location of the stabilized bars. The flow became constricted at the bars, and there the single inner channel was narrow and deep. Where crossings existed originally, erosion was least, and where the flow exited from a constriction, more erosional forms and multiple grooves developed, but they were less deep than at the constrictions.

In a sinuous, low width-depth—ratio channel excavated in bedrock, erosion again occurred more at bends than at crossings. At bends, bottom erosion was initially more pronounced at the convex bank, but after gradient decreased and deposition began, erosion was greater at the concave bank. Lateral versus vertical incision was controlled by the amount of load entrained by the flow, with corrasion producing a marked erosional effect at the insides of bends. It is significant that the Denwa River at several locations hugs the inside of its highly sinuous meanders (Fig. 20) in a manner identical to the experimental results described previously.

Figure 20. Photographic view of incised meanders on the Denwa River, Pachmarhi. It appears that an earlier period of lateral incision, evidenced by slip-off slopes at the insides of bends in the upper strata, has been replaced by vertical incision, indicated by steep convex banks at bends where the channel hugs the insides. This corresponds to experimental channel four, when the greatest incision was at the inside of a bend until sediment began to be deposited.

If bedrock resistance controls the amount of load entrained in an incising channel, Moore's conclusions seem to be correct, with one qualification. That is, for vertical incision to occur as a result of a tectonic slope increase, entrainment of all available sediment load is required. Base-level recession could also result in vertical incision, but this was not investigated in the present study.It was not possible to maintain appropriate model-prototype ratios among the many morphologic and hydraulic variables during experimentation; nevertheless, the general correspondence between the experimental results and field situations indicates that simple experimental approaches to complex morphologic problems can provide new information of value in the interpretation of natural phenomena.

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