EQUILIBRIUM CONDITION AND SEDIMENT TRANSPORT IN AN EPHEMERAL MOUNTAIN STREAM

by

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ABSTRACT

Flow frequency curves supported the hypothesis that channel-forming flows are exceptional events in ephemeral mountain streams. This was substantiated by the lack of a relationship between sediment production and sediment yield. Numerous bed nickpoints indicated channel instability, despite gravel bars and log steps that are part of the slope adjustment processes. Due to differences in structural density between bars and steps, size distribution of the sediment deposits above them differs. Although only qualitative guidelines are presented, the watershed or wildlife manager should be in a position to utilize the formation of gravel bars and log steps for his management goals.

PAST RESEARCH

My research in the high Rocky Mountains of Colorado has shown that perennial mountain streams, surrounded by forests, not only establish gravel bars on their beds but also incorporate into their channels large forest debris such as logs and branches (Heede 1972). These log steps and gravel bars are a means of adjustment to slope by the stream. That both steps and bars become an integral part of the hydraulic geometry is illustrated by two facts: (1) more bars and steps are formed on steeper channel gradients than on gentler ones, and (2) fewer gravel bars are formed where a greater number of log steps exist. Aspects of hydraulic geometry such as longitudinal profile, width-depth relations between stations, and sediment movement, indicated the Colorado streams were in dynamic equilibrium.

In contrast, our research on ephemeral North and South Forks of Thomas Creek, in Arizona's White Mountains, strongly indicated that these streams were not in dynamic equilibrium. Relationships between gravel bars and log steps could not be established, probably because numerous channel nickpoints destroyed bars and steps during their upstream advance. Thus, the nickpoints played a stronger role in stream adjustment to slope than did the bars.

The longitudinal profiles of the streams showed a strong tendency toward convexity. Structural geologic controls, such as differences in erosion resistance of the bed rock along the thalweg, could not be detected to explain the long convex profiles. Nor could sufficiently large changes in width-depth ratios be established to suggest drastic differences in required energy expenditures by the streams. Yet, numerous fissures in the volcanic bed rock, a by-product from a nearby fault, led to streamflow losses at some stations and gains at others. It is postulated that bed nickpoint advances, plus a pronounced head cut signifying the start of the channel bed about half way upstream on the watershed, are responsible for lack of dynamic equilibrium.

OBJECTIVES

Present research is concentrated on an ephemeral stream located two airmiles from Thomas Creek. Objectives are to determine the stage of development relative to equilibrium, and to compare conditions and hydraulic processes with those of Thomas Creek. Furthermore, the role of gravel bars and log steps in the sedimentation processes are being explored.

STUDY STREAM

The experimental watershed of Willow Creek's West Fork covers 290 acres. Yearly precipitation averaged 28.8 inches during the last 16 years, fluctuating between 20 and 43 inches (Rich and Thompson 1974). About 50 percent falls during the winter months—October through May—the rest during the remainder of the year. Streamflow occurs only during spring snowmelt and at times of intense summer storms. During 13 years of record, flow discharge attained an average maximum yearly peak of 1.52 cubic feet per second (c.f.s.). Normally, peak flows are somewhat higher during snowmelt with a yearly average of 1.88 c.f.s.

The watershed is located at an altitude of about 9000 ft in virgin, over-mature southwestern mixed conifer forest. Land management activities on the watershed are restricted to fire protection. Large amounts of forest debris cover the forest floor as well as banks and bed of the stream. Nearby South Fork of Thomas Creek, surrounded by a comparable forest at similar altitude, averaged about 10 tons per acre of forest debris larger than 3 inches in diameter[1/]. The sampling area included 10- to 15-ft-wide

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1/ Survey by S. Sackett and J. Dieterich. Office File Report Rocky Mt. For. and Range Exp. Stn., Tempe, Arizona, 1974.

strips adjacent to the channel banks. Thus many logs and large branches are available to the stream for the formation of steps. However, the stream also runs through some open meadows. The meadows represent flood plains, formed by shifting flows. Typically, narrow V-shaped valley sections are found immediately downstream from the meadows.

The geologic formations are of volcanic origin, and consist of basalts, breccia, and cinders in alternating bands to a total depth of several thousand feet. Soils along the channel bed generally are high in organic material. Gravel (material not passing through a 2 mm-sieve) makes up 55.7 percent by weight of the surface soils. The average size distribution of the soils by percent is: sand 23.2, silt 32.9, and clay 43.9.

FLOW FREQUENCIES

During the last 10 years of record, West Willow Creek had a dry channel 3 percent of the time. The dryness was confined to only 2 years. ("Dryness" was defined as a period of more than 6 consecutive dry days.)

In contrast, the Thomas Creeks were dry 14 percent of the time during the same period—nearly 5 times longer than Willow Creek. From these statistics, one could conclude that Willow Creek is almost a perennial stream, and Thomas Creeks were correctly classified as ephemeral streams (Heede 1975).

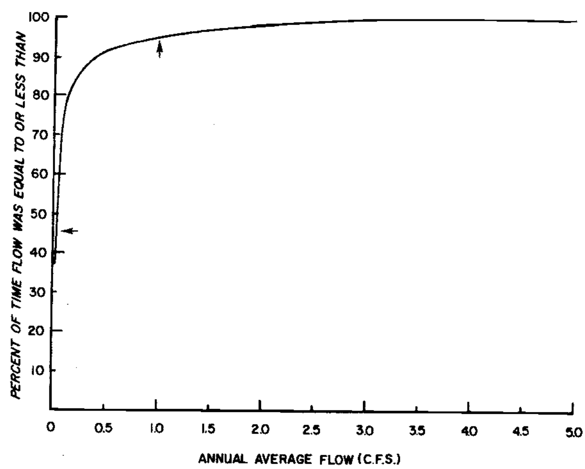

Figure 1. Flow frequency of West Willow Creek, White Mountains, 1966-75. Arrows refer to discussion in text.

An evaluation of energy expenditures also requires examination of frequencies of flow magnitudes (fig. 1). Thus during the 10-yr period, 46 percent of the time Willow Creek carried less than 0.02 c.f.s., and experienced flows of $\geq$ 1 c.f.s. only 5 percent of the period. The Thomas Creeks have even longer low-flow periods (64 percent) but similar periods for flows $\geq$ 1 c.f.s.

HYDRAULIC GEOMETRY

The longitudinal profile of West Willow Creek can be closely represented by a straight line with the exception of the lower reach. This reach is convex, and has a much gentler average bed gradient than the upper reach (0.036 versus 0.062 ft/ft). The reaches are separated by a road. At the road crossing, the stream flows through a culvert. Almost the total length of the lower reach is embedded in a meadow, a deposition feature as described earlier. The upper reach is located in a V-shaped valley with a narrow bottom. A few small flood plains, covering individual areas each not larger than a few hundred ft^2, are the exception.

The shape of Willow Creek's long profile differs drastically from that of the Thomas Creeks, which are highly convex (Heede 1975). Differences in profiles are also apparent in the type of beginning of channelization. While the Thomas Creeks begin with an abrupt head cut on the valley floor, Willow Creek's headwater drains gently into the gradually incised bed.

Numerous gravel bars and log steps cover the beds of the Thomas Creeks. Logs and branches fell into the channel, and with time, became incorporated into the bed. They now act as small dams that provide overfalls for low flows and accumulate sediment. Rotting processes and exceptionally large flows remove some dams, but other logs, falling at random, take their place. The bars and steps did neither adjust to the channel gradient nor to each other.

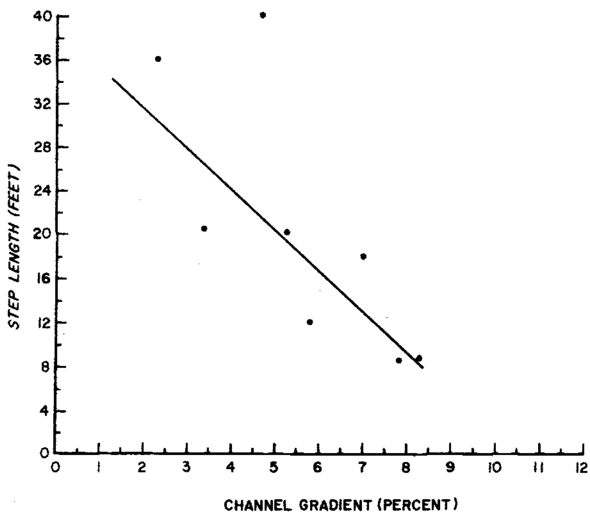

Figure 2. Relationship of step length to channel gradient in ephemeral West Willow Creek. Step length refers to distance between gravel bars and/or log steps.

In contrast to the Thomas Creeks, gravel bars and log steps of Willow Creek have adjusted to the bed gradient and to each other. Adjustment to slope is illustrated by figure 2, which shows that step length between bars and logs decreases with increasing gradient. Adjustment between these bed features is indicated by the fact that more bars formed if less logs were available. Thus in the upper reach of Willow Creek, 72 percent of all structures were logs (totaling 140) and only 54 gravel bars had to be formed. In the lower reach, on the other hand, only 23 logs were available, and 65 percent of the structures were stream-generated gravel bars.

Roots exposed on the bed and channel nickpoints formed steps similar to logs and bars. Large roots generally are solidly anchored into both banks, and thus are quickly undercut by channel degradation processes. Their influence vanishes rapidly, therefore, in contrast to logs that change their position with the bed. Most roots crossing our study streams were of little consequence.

Channel nickpoints, however, are very active agents in the slope adjustment processes. Nickpoints are scarps on the bed that represent abrupt slope gradient changes. These points advance upstream to extend the lower gradient toward the headwater. They must be regarded as critical locations for sediment production but they also dissipate flow energy. Since the average height of the nickpoints in Willow Creek is 0.66 ft, and since flows seldom exceed depths of 0.4 ft, most nickpoints are seldom submerged, and they normally function as flow energy dissipators. Even submerged nickpoints would add to channel roughness.

The total fall of a stream can be expressed in terms of potential energy. Because the combined height of all gravel bars, log steps, and nickpoints amounts to 76 percent of the total fall, the potential energy reduction is substantial. Of this reduction, nickpoints are responsible for only 9 percent.

SEDIMENT MOVEMENT AND DEPOSITION

Gravel bars and log steps influence sediment transport in several ways. Both provide basins for sediment deposition. The deposits build up to a gentler gradient than the original bed, and the channel bottom widens. Those changes lead to reduced flow velocities on the deposits, resulting in reduced sediment transport. Bars and steps also reinforce the channel, thereby decreasing sediment production above the structures.

Because structural density differs between these types of barriers, differences in sediment deposit characteristics must be expected. Bars have more and larger openings than log steps. This dissimilarity was reflected in the sediment size distribution. Incorporated organic material was considered part of the soils (fines). Soils accounted for only 35.2 percent of the deposits at rock bars, but 67.7 percent at log steps. The remainder was gravel ($\geq$ 2mm). The difference in the size distribution was highly significant.

Comparison of the average channel gradient, derived from the total fall, with the average deposit gradient above bars and steps yielded a reduction from 0.051 to 0.013 ft/ft, representing a decrease of about 75 percent. In terms of velocity and load-carrying capacity, this decrease is substantial.

Stability investigations showed that, of a total of 170 log steps, 77 percent were fully and 14 percent partially intact. In all cases, the loss of stability was due to rotting of the wood.

DISCUSSION AND CONCLUSIONS

The comparisons of dry-channel and low-flow periods between the Thomas Creeks and Willow Creek indicated that the latter is indeed a more "vigorous" stream, especially if we consider that its watershed area is only about half that of the individual Thomas Creeks. But in Willow as well as in Thomas Creeks, channel-forming flows are sporadic events. These flows occurred more frequently during the wet water-year of 1973, when an exceptional peak flow of 16.8 c.f.s. was measured in Willow Creek. In this stream, only 17 percent of the peak flows were larger than 2 c.f.s. during the past 10 years, and 9 of these (12 percent) took place in 1973.

Numerous boulder-strewn reaches in both streams support the conclusion that the truly channel-forming flows are exceptional events. These reaches are responsible for the sediment transport characteristics of ephemeral streams that contrast with those of perennial streams. Relationships between sediment production and sediment yield are not clearly established in ephemeral or partially ephemeral streams, because the sediment produced within the system may not appear at a given station for some time in spite of high production rates. High rates may be indicated by channel nickpoints and their upstream advance, bank cavings, point bars, cross-over bars, or other deposition features on the bed. In both ephemeral and perennial streams, scour alternates with deposition along the length of the thalweg. But while sediment is transported continuously throughout the system in perennial streams, it may move only spasmodically over short distances in ephemeral streams. Since the sediment is carried downstream stepwise, eventually it will either be deposited at the mouth of the stream, or a flow of exceptional magnitude may flush out the channel, carrying most of the available sediment completely through the system.

If we evaluate the longitudinal profile of Willow Creek, we must recognize that the road crossing constitutes a control for further profile developments. It can be assumed that this control has not greatly influenced the present profile because the crossing was established only 12 years ago. The drastic break in gradient between downstream and upstream reach should be attributed to the extensive deposition on the meadow below the road and not to the crossing itself. Undoubtedly, the bulk of this deposit was laid down during periglacial times and not by the present stream. Valley narrowing by protruding mountain spurs facilitated the deposition.

Geologic controls, such as changes in rock formation (rock hardness) or structure, do not occur in the upstream reach. Its long, straight profile is primarily the result of stream action. This profile is closer to the ideal concave profile that is often characteristic of streams in dynamic equilibrium. If this implication is correct, it would mean that Willow Creek is closer to dynamic equilibrium than the Thomas Creeks with their convex profiles. However, the occurrence of numerous nickpoints in our study stream shows clearly that dynamic equilibrium has not yet been fully attained. Nickpoints are active agents in the processes of slope adjustment and thus can cause drastic profile shape changes. Furthermore, they are locations of intense sediment production, which is not generated under dynamic equilibrium.

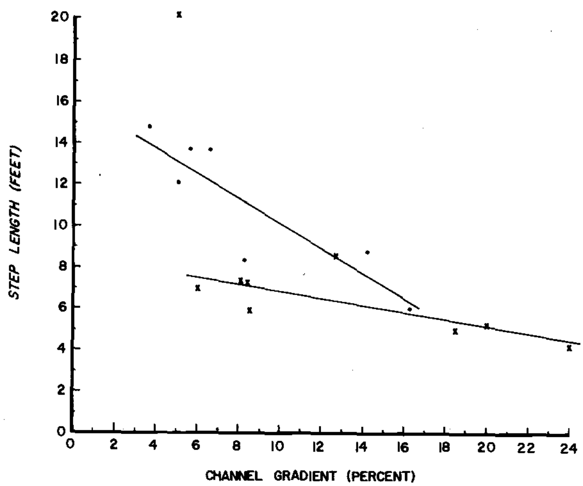

Figure 3. Relationship of step length to channel gradient in two perennial Rocky Mountain streams.

Longer periods of flow and shorter periods of low flows give Willow Creek a developmental advantage over the other two streams. This advantage seems to be expressed also in the relationship between step length and channel gradient (fig. 2). That relationship was established for Rocky Mountain streams (fig. 3) in dynamic equilibrium (Heede 1972), but was not present at the Thomas Creeks.

Prevailaing low-flow conditions did not permit establishment of hydraulic flow parameters such as width-depth ratios or shape factors. Stream hydraulics are an integral part of any evaluation of equilibrium, and our postulate should therefore be considered in this light.

MANAGEMENT IMPLICATIONS

At this state of our knowledge, the manager should focus on the frequency of nickpoints in a system. Frequent nickpoints should warn him of instable conditions. For example, average distance between nickpoints was 236 ft in Willow Creek, indicating instability.

Management implications of gravel bar and log step relationships are manifold. For instance, log steps collect more fine sediments than do bars. Thus, if a management goal is to reduce fine sediment transport for fishery or other reasons, the number of log steps should be increased by silvicultural practices such as leaving more dead and dying trees alongside a stream. In time, the number of gravel bars would decrease, because less bars will be formed if more logs are available.

Our present research results do not permit us to establish quantitative guides on numbers of trees to be left or cut to cause sediment transport changes through changes in bar-step relations. Neither can threshold values be given that separate conditions of sediment movement reduction from those of increase. Only some obvious general rules can be stated:

1. Dead and dying trees should not be left in patches, because of the danger of log jam formation. Larger flows break such jams with devastating results.

2. Elimination of log steps is not a desirable goal, because all trees would have to be removed from the stream banks. This would decrease erosion resistance of the banks.

3. It is desirable to leave some large, nonmerchantable trees along stream banks. These trees will not only feed some logs to the stream to replace rotten log steps, but will also provide favorable habitat for birds and small mammals.

REFERENCES CITED

Heede, Burchard H. 1972. Influences of a forest on the hydraulic geometry of two mountain streams. Water Resour. Bull. 8(3):523-530.

Heede, Burchard H. 1975. Mountain watersheds and dynamic equilibrium. Watershed Manage. Proceed. Symp. ASCE Irrig. and Drainage Div., Aug. 11-13, Logan, Utah.

Rich, Lowell R. and J. R. Thompson. 1974. Watershed management in Arizona's mixed conifer forests: The status of our knowledge. USDA For. Serv. Res. Pap. RM-130, 15 p. Rocky Mt. For. and Range Exp. Sta., Fort Collins, Colo.