# Pools, Riffles, and Channelization

Edward A. Keller

Environmental Studies and Department of Geological Sciences, University of California, Santa Barbara, CA 93106

ABSTRACT / The addition of regularly spaced deeps (pools) and shallows (riffles) that provide a variety of flow conditions, areal sorting of stream-bed material, cover for wildlife, and a positive aesthetic experience, may be desirable in many channel projects. Such designs will reduce adverse environmental impacts of stream channel modifications.

Analysis of variance for pool-to-pool spacing data suggests that there is no significant difference with respect to channel width between pools that form in natural streams and those in streams affected by a variety of human uses. Short of channelization, which changes the channel width, pools and riffles, within limits, are not particularly sensitive to environmental stress.

Experiments in Gum Branch near Charlotte, North Carolina, support the hypothesis that channel form and process evolve in harmony and that manipulation of cross-channel morphology can influence the development of desired channel processes. Planned manipulation of its channel form induced Gum Branch to develop as desired. Morphologic stability consisting of incipient point bars, pools, and riffles was maintained over a period of high magnitude flood events, only to be degraded later by a wave of sediment derived from upstream construction and stream-bank failures. Thus, environmentally desirable channel morphology in urban streams cannot remain stable if changes in the sediment load or storm-water runoff exceed the limits of the stream's ability to make internal adjustments while maintaining morphologic stability.

Environmental Geology, Vol. 2 No. 2 pp. 119–127

## Introduction

Channelization is an engineering practice that often involves straightening, deepening, or widening of a natural or previously modified stream channel. It may include implacement of riprap or a concrete lining to protect the channel bed and bank from erosion. Although many channelized streams function as designed from an engineering standpoint, there is considerable objection to the associated environmental degradation. In some instances the engineering design is inadequate, resulting in severe bank erosion and other stability problems (Daniels 1960, Emerson 1971, Yearke 1971, Morisawa and Vemuri 1975). However, the pressure to modify streams will increase rather than decrease and new design criteria must be established to reduce environmental disruption. This will require multi-objective planning as envisioned by Morisawa and Vemuri (1975) and application of data on natural fluvial processes to the design of channels (Keller 1975 and 1976, and Morisawa 1976).

Designing streams to complement natural processes rather than absolutely controlling them is at the heart of the school of environmental planning that strives to "design with nature" (McHarg 1971). Such planning employs a form of environmental determinism that recognizes streams as systems capable of internal self-adjustment. That is, changes, within limits, may be accommodated without serious environmental degradation (Leopold 1977).

Aspects of a natural fluvial system that eventually may be used to reduce environmental degradation in channel works (Keller 1976) are: 1) recognition that the riverine environment (channel and flood plain) is an open system tending toward a dynamic or quasi-equilibrium in which there is a rough balance between the load imposed and work done such that channel form and fluvial processes are interdependent; 2) recognition that flow in natural streams is characterized by a downstream alternating convergence and divergence of flow that facilitates morphologic stability, development of pools and riffles, and channel maintenance; 3) recognition of the existence of geomorphic thresholds that partially control erosion, deposition, and channel patterns; and 4) recognition of complex relations between erosion, deposition, and sediment concentration that influence channel stability.

Unfortunately not all aspects of the regimes of natural streams are sufficiently understood to be incorporated into new design criteria. Until the behavior of streams is better understood the best course of action may be to proceed with channel modification only where it is absolutely necessary and to confine the practice to the shortest possible length of the channel with the least possible amount of artificial control (Keller 1976).

The importance of a variety of low flow conditions alternating from slow deep water in pools to faster shallow water on riffles is fairly well documented (Corning 1975, Eiserman and others 1975). Pools and riffles are important to the welfare of game fish because they provide areas for feeding, breeding, and cover. Pools tend to scour at high flow and fill at low flow, whereas

0099-0094/78/0002-0119 $1.80

riffles may scour at low flow and fill at high flow (Keller 1971, Andrews 1976). This pattern of scour and fill is significant in maintaining the morphology of the pool-riffle sequence and in providing such a natural sorting of the bed material that the coarser material is deposited on riffles and point bars. This sorting provides a quality environment for bottom-dwelling organisms that, in turn, are food for fish and other animals.

Before pools and riffles can be included in the design criteria for channel work it is essential to evaluate the ability of these bedforms to withstand environmental stress. Riffles have been successfully built in gravel-bed streams to improve trout and salmon habitat (Stuart 1953) and pools and riffles have been observed to form in some streams following channelization (Morisawa and Vemuri 1975); however, little has been reported on the variability of the pools and riffles in streams modified by a variety of human uses. Furthermore, the concept of constructing pools and riffles implies that a deliberate modification of channel form can physically change the fluvial processes that produce desired variation of flow and erosion-deposition patterns. This point is not intuitively obvious.

The purposes of this paper are to examine the variability of pool-riffle development in streams subject to a variety of uses with varying imposed conditions; and to examine the hypothesis that fluvial processes can be partially controlled by changing the channel morphology. Pool-riffle development will be evaluated by comparing the distribution of pool-to-pool spacing in streams affected by human use with natural streams. Morphology-process relations will be tested by evaluating channel manipulation experiments on Gum Branch, a small stream near Charlotte, North Carolina.

## Pools, Riffles, and Human Use

Pools and riffles are very common bedforms in gravel-bed, alluvial stream channels. The spacing of successive pools is generally consistent at 5–7 channel widths (Leopold and others 1964, Keller 1972). In order to evaluate the sensitivity of pools and riffles to human use of a stream, the characteristic pool-to-pool spacing was measured in four streams: Boone Fork and Sims Creek near Blowing Rock, North Carolina; McAlpine Creek near Charlotte, North Carolina, and Durkee Run in Lafayette, Indiana.

Boone Fork, directly below Price Lake Dam, is affected by the direct overflow structure constructed from 1958 to 1960. In spite of this structure, well developed pools and riffles exist. Sims Creek is a tributary to Boone Fork below Price Lake Dam. The stream meanders through a picnic ground constructed in 1964–1965. Although considerable bank vegetation was removed or disturbed, well developed pool-riffle sequences exist (Fig. 1).

McAlpine Creek was channelized approximately 25 years ago. However, in the study reach directly downstream from Independence Avenue, Charlotte, North Carolina, a series of pools and riffles have developed in the straight channel. The existence (recovery?) of the pools and riffles probably results from the fact that even though McAlpine Creek was straightened, its channel slope (0.001) is relatively low. Furthermore, riffle development of McAlpine Creek is facilitated in several instances by fortuitous location of bedrock outcrops. However, many channelized streams do not show the morphologic recovery observed in McAlpine Creek (Keller 1975). For example, in the channelized reach of Mallard Creek, near Harrisburg, North Carolina, the

**Figure 1.** Well developed pool-riffle sequences in Sims Creek near Blowing Rock, North Carolina.

Table 1 Summary of Channel Characteristics

| | Type of stream | Bed and bank material | Sinuosity | Channel width (meters) | Channel slope | Average pool-to-pool spacing in channel widths | N* |
|---|---|---|---|---|---|---|---|
| Boone Fork, near Blowing Rock, North Carolina | Perennial: below Price Lake Dam | Alluvial (little bedrock) | 1.25 | 9.46 | 0.0045 | 4.90 | 14 |
| Dry Creek, near Winters, California | Intermittent | Alluvial (some partial consolidation) | 2.40 | 10.07 | 0.0025 | 5.92 | 38 |
| Durkee Run Lafayette, Indiana | Intermittent: urban influence | Alluvial | 1.13 | 4.27 | 0.0023 | 5.56 | 33 |
| McAlpine Creek, near Charlotte, North Carolina | Perennial: channelized approx. 25 yrs ago | Alluvial (little bedrock) | 1.01 | 6.03 | 0.0010 | 6.74 | 18 |
| Sims Creek, near Blowing Rock, North Carolina | Perennial: some bank vegetation removed for park development | Alluvial | 1.31 | 3.66 | 0.0049 | 5.52 | 20 |
| Wea Creek, near Lafayette, Indiana | Perennial | Alluvial | 1.38 | 20.44 | 0.0015 | 5.25 | 16 |
| Wildcat Creek, near Dayton, Indiana | Perennial | Alluvial | 1.42 | 25.01 | 0.0014 | 5.01 | 30 |

*N is the number of pool-riffle sequences sampled.

pools are poorly formed and spaced relatively far apart, averaging 7.7 times the channel width. On the other hand, the pool-to-pool spacing in the natural reaches of Mallard Creek average 5.3 times the channel width and are well developed with banks defended by extensive root systems of large trees.

Durkee Run meanders through residential and commercial developments. The channel is characterized by numerous well developed pool-riffle sequences.

The research design to evaluate the pools and riffles (Keller and Melhorn, in press) consists of comparing the distribution of pool-to-pool spacing for the streams affected by human use with several natural alluvial streams. Stream characteristics, including 169 pool-to-pool spacings in seven streams were measured (Table 1). The field technique was to measure the distance along the stream between successive pools and divide this distance by the channel width of that reach. Thus the pool-to-pool spacing is reported in channel widths, which allows comparison of streams of various sizes. The measurements were taken at low flow. The lowest point (area of deepest water) in the pools is a reference point from which measurements were taken. Channel width is the width of the bed material taken at the riffle between pools being measured. Data from the seven streams suggest that for these streams this width is near the bank-full width. Channel width was measured at riffles because the channel cross-section is generally symmetrical at riffles and the banks well defined.

The distributions of pool-to-pool spacing data for the seven streams are shown on Fig. 2. Comparison of these distributions is accomplished by statistically evaluating the variance of the spacing of pools. However, analysis of variance assumes the data are normally distributed. The Kolmogorov-Smirnov Goodness of Fit Test (Table 2) was applied to tests for normality. The test compares the distribution of pool-to-pool data with the normal distribution. For all streams the null hypothesis of no significant difference is accepted. Analysis of variance (Table 3) suggests there is no significant difference between the pool-to-pool spacing for the "natural" streams and those affected by varying human use. Thus it appears that for the streams evaluated, pools and riffles are not particularly sensitive to environmental stress

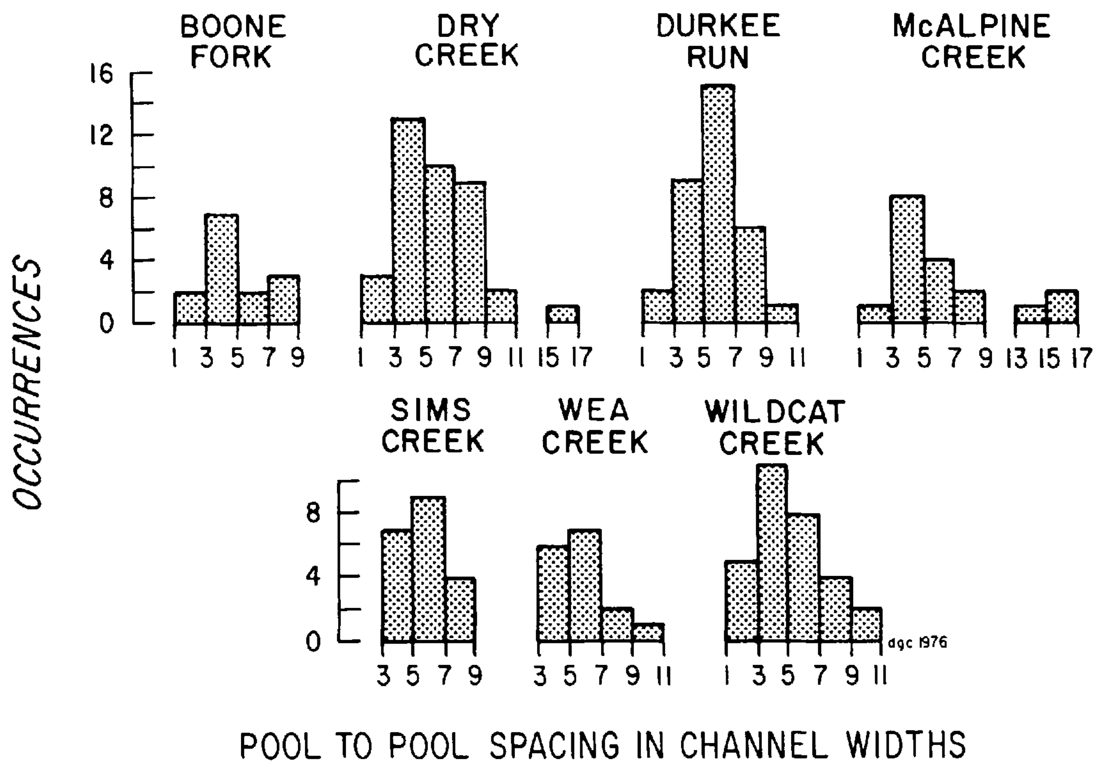


**Figure 2.** Distribution of pool-to-pool spacing for the seven streams evaluated

and may exist with a variety of man-induced constraints. However, the pool-riffle sequence is very sensitive to channel width; channelization that changes the width of the stream will alter the pool-riffle environment.

It is important to determine accurately what specific conditions are necessary for pools and riffles to develop and be maintained. Channel slope, sediment concentration, and size of the bed material have long been recognized as important aspects of morphologic stability (Lokhtine 1909). The study of gravel-bed streams suggests that pools and riffles develop on slopes of 0.005 or less (Table 1). Thus a gravel-bed stream with an initial slope of 0.0025 should not be shortened more than 50 percent if pools and riffles are desired. The upper limit of channel slope at 0.005 is considered conservative and, with more data, it may be shown that some streams with a slope approaching 0.008 or even 0.01 may have stable pools and riffles (Keller 1975).

Other factors affecting the stability of pools and riffles include the nature of the banks and the effect of vegetation in stabilizing them. Cohesive bank materials coarser or finer than sand favor stability, as do trees with extensive root systems that protect the banks from erosion. In urbanizing watersheds the situation is further complicated by highly variable sediment loads and channel-forming flows. High sediment loads tend to fill pools and bury pool-riffle sequences, whereas frequent high-magnitude flows wash them out.

### Channel Form-Process Experiments

If one accepts the postulate that streams are open systems in which equilibrium is achieved relatively quickly, one must recognize that channel form and process are opposite sides of the same coin. Because they are interdependent the entire fluvial system tends to evolve in harmony. There is no doubt that changing the intensity or frequency of a process changes the channel form. Most adverse effects of channelization on the riverine environment occur because of changes in the channel form (shortening, deepening, or widening) and changes in response (additional runoff with less lag time between rainfall and flow concentration, for example).

Natural, meandering, gravel-bed streams tend to be characterized by channel cross-sections that alternate from asymmetric (pools) to symmetric (riffles). The regular changes in the shape of the channel facilitate, at bank-full stage, a convergence of flow accompanied by scour in pools, and a divergence of flow with deposition on riffles (Leliavsky 1894, Keller and Melhorn 1973).

Table 2 Kolmogorov-Smirnov Goodness of Fit (normality) for Pool-to-Pool Spacing

| | n | $\sigma$ | $\bar{x}$ | Dm | Dc (0.05L/S) | $H_0$* accepted |
|---|---|---|---|---|---|---|
| Boone Fork, North Carolina | 14 | 1.65 | 4.90 | 0.12 | 0.35 | yes |
| Dry Creek, California | 38 | 2.74 | 5.92 | 0.05 | 0.22 | yes |
| Durkee Run, Indiana | 33 | 1.69 | 5.56 | 0.04 | 0.23 | yes |
| McAlpine Creek, North Carolina | 18 | 4.15 | 6.74 | 0.20 | 0.31 | yes |
| Sims Creek, North Carolina | 20 | 1.30 | 5.52 | 0.04 | 0.29 | yes |
| Wea Creek, Indiana | 16 | 1.88 | 5.52 | 0.12 | 0.33 | yes |
| Wildcat Creek, Indiana | 30 | 2.31 | 5.01 | 0.03 | 0.24 | yes |

*$H_0$ (null hypothesis): There is no difference between the observed distribution of spacing of pools and the theoretical (expected) normal distribution.

N = sample size

$\sigma$ = standard deviation

$\bar{x}$ = mean

Dm = maximum deviation (by class intervals) between the sample distribution and normal distribution

Dc = critical deviation for a significant difference

Table 3 Analysis of Variance for Pool-to-Pool Spacing

| Source of variation | d.f. | Sum of squares | Mean square | F | Decision |
|---|---|---|---|---|---|
| Between-groups | 6 | 46.8 | 7.80 | 1.35 | Accept $H_0$* |
| Within-groups | 162 | 938.3 | 5.79 | | |
| Total about x | 168 | 985.1 | | | |

*$H_0$ (null hypothesis): There is no significant difference in the mean spacing of pools of our seven sample streams.

"$\beta$" error type II—accepting a false hypothesis—chance decreases as "N" increases. $F_c$ (0.05;6,162) = 2.16

$\alpha$ = 0.05 minimizes chance of $\beta$ error.

For physical, biological, and aesthetic reasons, it is desirable to design man-altered channels to converge and diverge flow similarly.

As a first step toward this, experiments in Gum Branch, a small stream (bed-width 5–6 m) near Charlotte, North Carolina that had been channelized approximately 25 years ago and was scheduled for additional work, were initiated in 1974. Prior to the channel work, the stream was a sediment-choked, brush-lined channel containing urban trash. The high resistance to flow induced by the brush, trash, and numerous large, closely spaced sandbars increased the urban flood hazard. The experiments are part of a long range research project to develop a channel restoration program for long neglected urban streams (Keller and Hoffman 1976 and in press).

The hypothesis tested in the Gum Branch experiments was: can modification of the cross-channel morphology partially control the behavior of the alluvial stream? Specifically, the research was designed to manipulate the cross-channel profiles to cause the stream to converge and diverge the flow as in natural streams, and thus induce the stream to develop a series of point bars in desired locations along 130 m of channel. No structures were used.

The original construction plan called for traditional channelization with a larger channel and trapezoidal cross-channel sections. The decision to try new design criteria was based on the idea that streams are a valuable resource and that urban communities should take advantage of their water resources rather than destroy them. A program of channel or stream restoration in combination with flood plain regulation and sediment control was initiated. The stream restoration program involves the application of natural fluvial processes to neglected urban streams such that a more functional and aesthetically pleasing riverine environment is developed (Keller and Hoffman 1976 and in press).

The Gum Branch experiments required a change from conventional channel engineering. For example, Fig. 3 shows the conventional long profile for the experimental reach of Gum Branch compared to the more detailed long profile along the thalweg (lowest elevation along the channel bottom in the downstream direction). The conventional long profile is produced by surveying the center line of the channel regardless of the channel morphology. The thalweg profile is significant because it shows areas of channel scour, which may be used in designing the variable channel cross-sections. Fig. 4 shows an idealized map of a channel morphology that was expected to develop by manipulating the channel cross-sections. Fig. 5 compares the original (preconstruction), conventional, and new design cross-channel profiles used in the Gum Branch experiment. Notice that the new design calls for two types of cross-channel profiles; symmetrical and asymmetrical. This is accomplished by varying the inclination of the channel bank from 2:1 to 3:1 (Figs. 4 and 5). The asymmetric cross-section should converge the high-flow water and cause scour near the bank with the 2:1 slope while facilitating deposition of a point bar in the bank with the 3:1 slope. The symmetric cross-profile with both channel banks at 2:1 is

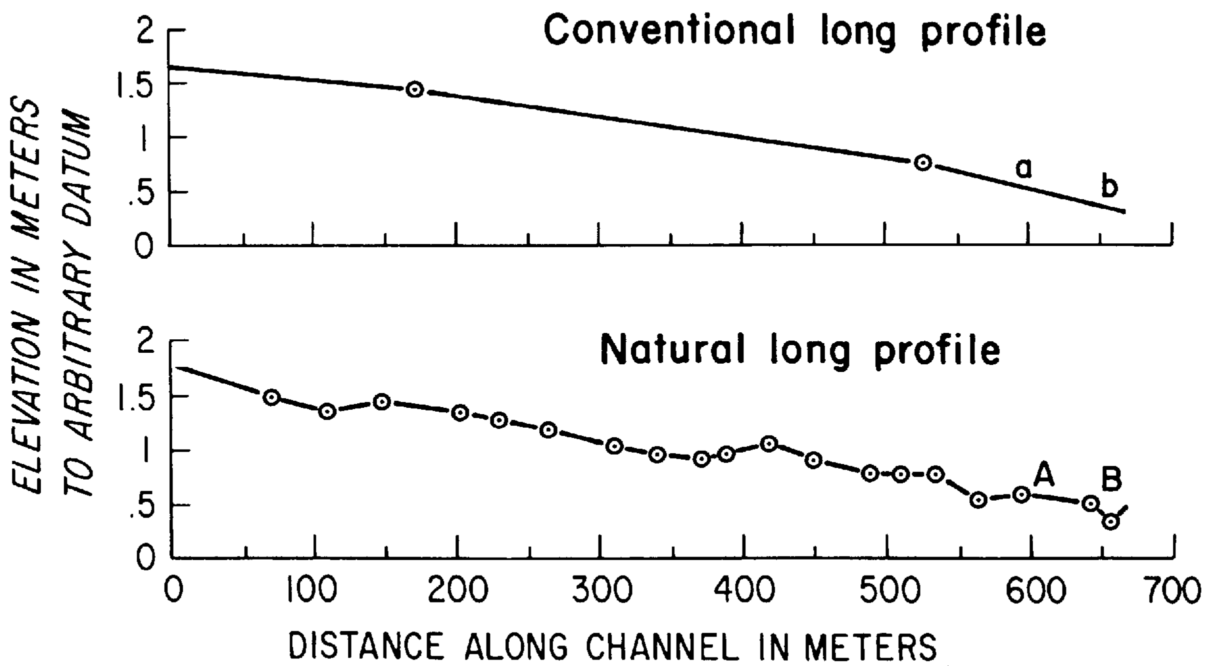


**Figure 3.** Comparison of a conventional long profile with the more detailed natural long profile of a short reach of Gum Branch. The letters a, b, A, and B are locational indicators for Figs. 4, 5, and 7.

designed to diverge flow. Thus the stream should be induced to construct a series of point bars and scour areas, similar to that found in natural streams. This effectively applies the hypothesis that modification of the channel morphology will induce deposition in desired areas.

Fig. 6 is a photograph of part of the experimental area shortly after construction. Notice the concordance between the design (Fig. 4) and the morphology actually produced by the interaction between channel morphology, running water, and moving sediment. The bars emerged following the first above normal flow after construction was completed. The bars formed adjacent to the bank with the 3:1 slope, where planned.

The next big question was—will the bars have morphologic stability? That is, will they remain in the same location during a series of flood events. Fig. 7 shows a series of cross-sections from April 1975 to October 1976. Morphologic stability was maintained from summer 1974 to fall 1975. During that period there were four overbank flows and the bars always emerged following the flood in the same relative positions. However, in late October 1975 the morphologic stability dissipated as the stream bottom was buried by an influx of sediment. The bars were buried by about 0.5 m of sand and fine gravel, and by summer 1977 the channel looked much as it did prior to the experiments.

The sediment that buried the designed morphology was derived in part from upstream construction and in part from upstream bank erosion following a storm in May 1975 in an area where the more conventional engineering channel design was employed. The cross-sections (Fig. 7) show that section A experienced no lateral bank erosion and section B migrated less than 1.0 m. However, section B is on a tight bend (Fig. 4) and some lateral erosion must be expected. Riprap is used where lateral migration must be controlled. Notice, however, that even with the lateral migration of section B, the morphology remained constant.

The conclusion drawn from the experiments on Gum Branch and on streams in Scotland (Stuart 1953) is that the concept that streams are open systems in which form and process evolve harmoniously is valid. Furthermore, manipulation of channel form may initiate processes that induce the stream to erode and deposit in desired locations. This conclusion, although tentative and in need of further verification, is significant relative to our attempts to construct pools and riffles in channel projects. However, the Gum Branch experience also illustrates the necessity of a sediment control and storm water management program in conjunction with the channel work. Without sediment and storm water control the channel morphology program is probably doomed to failure.

## Summary

The importance of the pool-riffle environment to wildlife and scenic resources is well established. What remains is to develop

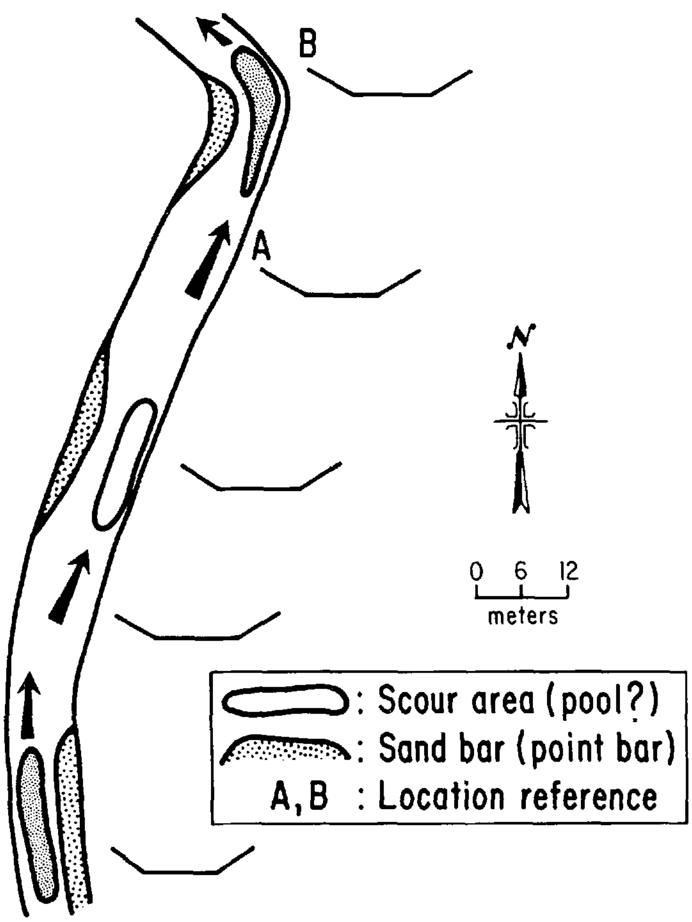


**Figure 4.** Idealized morphologic map showing desired channel morphology planned for by manipulating the cross-channel profiles in Gum Branch. Letters A and B correspond to locations on Fig. 3.

flexible new design criteria for channelization that will provide maximum utility of water resources while reducing environmental degradation. In some instances this may include planning and construction of pools and riffles or at least a diversity of flow conditions that simulate these forms. This involves application of natural fluvial processes to channel design, that is, designing with nature.

Statistical comparison of pool spacing with channel width in natural streams and those affected by limited human use suggests that there is no significant difference. This supports the tentative conclusion that the tendency for pools and riffles to develop is a fundamental aspect of stream channel morphology that is relatively insensitive to limited environmental stress. This conclusion is crucial if pools and riffles are to be included in design criteria for selected channelization projects. However, pools and riffles will not be stable in all streams. Channel stability is particularly troublesome in streams in which channelization, urbanization, or other rapid land-use changes significantly alter channel slope, width, depth, sediment load, or discharge. Furthermore, geomorphic thresholds that control the development of these rhythmic channel forms have not been completely delineated. In spite of this, many channelization projects on streams with a gravel bed and a final channel slope of less than 0.005 will have provided increased biologic productivity and scenic amenities by the addition of pools and riffles in the designed channel.

The channel experiments in Gum Branch help formulate a program of channel restoration for urban streams. The new program involves the manipulation of channel cross-section at desired locations to induce the stream to converge and diverge flow in a natural way. In conjunction with the manipulation of the stream cross-sections, sound conservation practices are applied

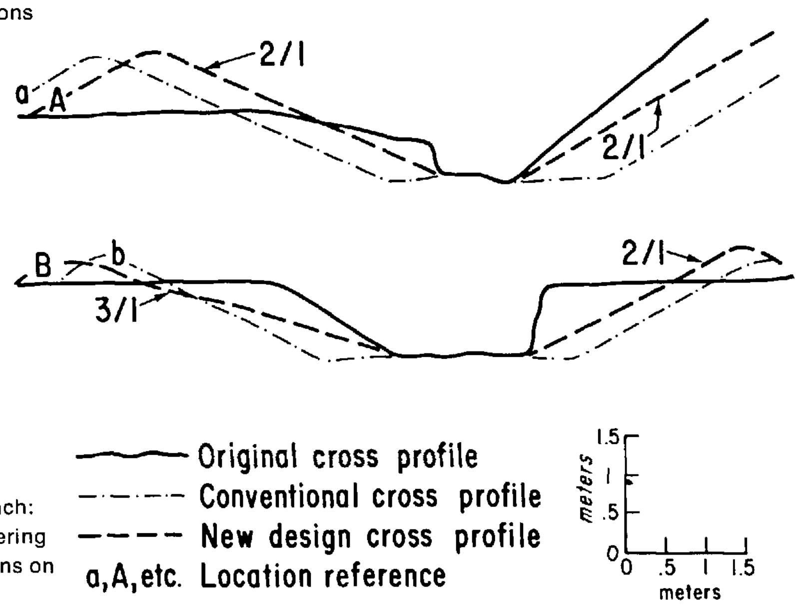


**Figure 5.** Comparison of cross-channel profiles in Gum Branch: conditions prior to channel modification; conventional engineering design; and new design. Letters a, b, A, and B refer to locations on Fig. 3.

**Figure 6.** Series of bars that developed in Gum Branch as designed. Compare the actual morphology with the idealized morphology of Fig. 4.

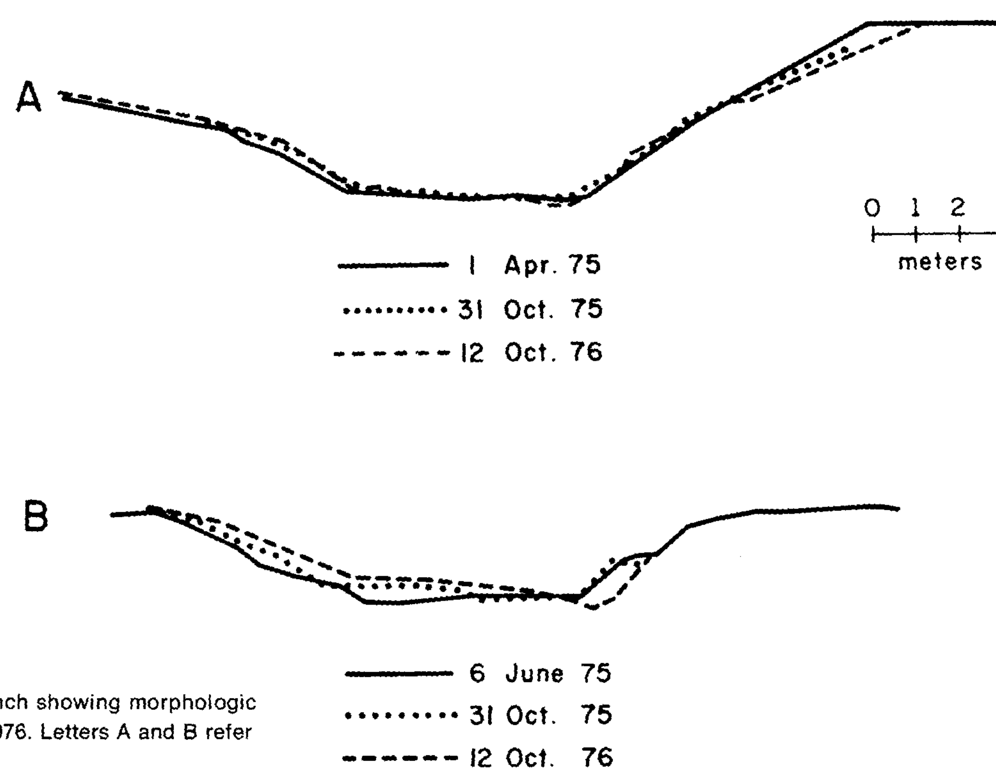


**Figure 7.** Cross-sections of Gum Branch showing morphologic change from April 1975 to October 1976. Letters A and B refer to locations on Fig. 3.

to the stream bottom and stream banks to reduce environmental degradation. Urban trash and large obstructions to flow are removed from the channel with as little disruption to the streambed as possible. Large trees on the banks of the channel are protected. In this way urban streams are designed to have an efficient flow and increased aesthetic appeal.

## ACKNOWLEDGMENTS

Assistance in the field by Mike Gardner and David Robinson is appreciated. Pool-to-pool spacing data for McAlpine and Mallard Creeks was collected by Mr. Robinson. Channelization research is sponsored by the University of North Carolina Water Resources Research Institute, Project B–089–NC.

## REFERENCES CITED

Andrews, E. D., 1976, River channel scour and fill: Geol. Soc. America, abstracts with programs, v. 8, no. 6, p. 755.

Corning, R. V., 1975, Channelization: shortcut to nowhere: Virginia Wildlife, Feb., p. 6–8.

Daniels, R. B., 1960, Entrenchment of the Willow Drainage Ditch, Harrison County, Iowa: Am. Jour. Sci., v. 258, p. 161–176.

Eiserman, F., G. Dern, and J. Doyle, 1975, Cold water stream handbook for Wyoming: U.S. Soil Conservation Service and Wyoming Game and Fish Department, 38 p.

Emerson, J. W., 1971, Channelization: a case study: Science, v. 173, p. 325–326.

Keller, E. A., 1976, Channelization: environmental, geomorphic and engineering aspects, *in* D. R. Coates (ed.), Geomorphology and engineering: Stroudsburg, Pennsylvania, Dowden Hutchinson and Ross Inc., p. 115–140.

———, 1975, Channelization: a search for a better way: Geology, v. 3, no. 5, p. 246–248.

———, 1972, Development of alluvial stream channels: a five-stage model: Geol. Soc. America Bull., v. 83, p. 1531–1536.

———, 1971, Areal sorting of bed-load material: the hypothesis of velocity reversal: Geol. Soc. America Bull., v. 82, p. 753–756.

———, and E. K. Hoffman, 1976, A sensible alternative to stream channelization: Public Works, Oct., p. 70–72.

———, in press, Urban streams: sensual blight or amenity: Jour. Soil and Water Conservation.

Keller, E. A., and W. N. Melhorn, 1973, Bedforms and fluvial processes in alluvial stream channels: selected observations, *in* M. Morisawa (ed.), Fluvial geomorphology: SUNY-Binghamton, N.Y., Proc. Fourth Annual Geomorphology Symposium, Pub. Geomorphology, p. 253–283.

———, in press, Rhythmic spacing and origin of pools and riffles: Geol. Soc. America Bull.

Leliavsky, de, N., 1894, *in* Leliavsky, S., 1966, An introduction to fluvial hydraulics: Dover, N.Y., p. 162–165.

Leopold, L. B., 1977, A reverence for rivers: Geology, v. 5, p. 429–430.

———, M. G. Wolman, and J. P. Miller, 1964, Fluvial processes in geomorphology: San Francisco, W. H. Freeman and Co., 522 p.

Lokhtine, 1909, *in* S. Leliavsky, 1966, An introduction to fluvial hydraulics: Dover, N.Y., p. 8–10.

McHarg, I. L., 1971, Design with nature: New York, Doubleday, p.

Morisawa, M., 1976, Channelization: impacts and solutions: Geol. Soc. America, abstracts with programs, v. 8, no. 6, p. 1019.

———, and R. Vemuri, 1975, Multi-objective planning and environmental evaluation of water resource systems: Final Report OWRT Project C–6065, 99 p.

Stuart, T. A., 1953, *in* L. B. Leopold, M. G. Wolman, and J. P. Miller, 1964, Fluvial processes in geomorphology: San Francisco, W. H. Freeman and Co., p. 206–208.

Yearke, L. W., 1971, River erosion due to channel relocation: Civil Eng., v. 41, p. 39–40.