# Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California

THOMAS E. LISLE *Pacific Southwest Forest and Range Experiment Station, United States Forest Service, Arcata, California 95521*

## ABSTRACT

**Jacoby Creek (bed width =12 m; bankfull discharge = 32.6 m$^3$/s) contains stationary gravel bars that have forms and positions controlled by numerous large streamside obstructions (bedrock outcrops, large woody debris, and rooted bank projections) and bedrock bends. Bank-projection width and bar volume measured in 104 channel segments 1 bed-width long are significantly cross-correlated at lags of -1, 3, and 4, indicating the tendency for large obstructions and bends to form bars 3 to 4 bed-widths downstream and 1 bed-width upstream. All of the 18 bars downstream of large obstructions or bends in the study reach were along the obstruction side of the channel or outside bank of the bend. Most of the pools (85%) were next to large obstructions or in bends; conversely, 92% of large obstructions or bends had pools. Comparison of the volume of four bars with volumetric bar changes and volume of bedload transported during four high-flow events suggests that rates of sediment transport were sufficient to cause major changes in bars during bankfull events. The only important channel changes observed in 4 yr, however, have been associated with the movement of large woody debris and with changes in the angle at which the flow approaches an obstruction.**

**A general model is proposed that large obstructions and non-alluvial bends stabilize the form and location of gravel bars. Bars are stabilized by two related mechanisms.**

**1. Large obstructions and bends cause intense, quasi-steady, secondary circulation in scour holes that terminate upstream bars at fixed locations. Obstruction width, channel deflection, scour-hole width, and bed width were measured at 26 obstructions. These data show that obstructions wider than approximately one-third of the bed form "pools" spanning the entire channel and, thus, terminating bars; smaller obstructions form "scour holes" contained within a single bar.**

**2. Bars are deposited upstream of large obstructions and sharp bends because of backwater reductions in stream power. Bars are deposited downstream because flow energy is expended around obstructions and bends and because the flow expands downstream of constrictions that result from large obstructions.**

**The formation of bars and pools inherent in many gravel channels can, thus, be enhanced and fixed in position by flow structures set up around large obstructions and bends formed of resistant materials.**

## INTRODUCTION

The study of self-formed alluvial channels has been essential to understanding how natural channels behave. Reaches of many streams, however, have non-alluvial boundaries composed of bedrock, colluvium, woody debris, or fabricated material. Usually more resistant than is alluvium, these materials commonly form sharp bends, promontories, and faces that present large, abrupt obstructions to the flow and thereby greatly affect channel-forming processes. Obstructions as geomorphic controls in channels (Matthes, 1947; Allen, 1982; Komar, 1983; Baker, 1984) have received little attention other than in studies of woody debris (Heede, 1972; Keller and Tally, 1979; Mosley, 1981; Beschta, in press; among others) and in studies of local scour around artificial structures (Laursen and Toch, 1956; Moore and Masch, 1965; Breusers and others, 1977; Baker, 1980; among others). Consequently, how obstructions affect the formation of channels and flood plains is neither well understood nor adequately recognized.

This paper describes how large obstructions and bedrock bends affect the channel of a gravel-bed stream in northern California. Local scour and deposition around frequent obstructions and bends form stable bar-pool topography and thereby control channel morphology. These observations suggest a general model for the stabilization of bar-pool topography by a series of obstructions of a minimum size.

## STUDY SITE: JACOBY CREEK

Jacoby Creek is a gravel-bed stream entering Humboldt Bay in north coastal California. At the downstream end of the 2.6-km study reach, the drainage area is 36 km$^2$; bankfull discharge is 32.6 m$^3$/s, and average bankfull depth is 1.0 m. Bed width (zone of annual bedload transport) averages 12 m. Stream gradient ranges from 0.014 in the upper end of the study reach to 0.006 in the lower end. Median grain size of the bed surface ($D_{50}$) is 40 mm; $D_{84}$ is 80 mm.

Sharp bends, formed most commonly against massive sandstone and mudstone outcrops of the Falor Formation (Manning and Ogle, 1950), separate reaches having low sinuosity (Fig. 1). Numerous obstructions projecting into the channel are formed by bedrock, root-defended bank promontories, and large woody debris contributed from a moderately dense stand of riparian trees (red alder, willow, big leaf maple, redwood, and Sitka spruce). Low-sinuosity reaches contain transverse (symmetrical) or diagonal (asymmetrical) bars; bends that have arcs greater than ~75° contain small point bars. ("Bar" refers to any bar extending across the entire channel bed and downstream a distance of at least one channel-width, unless otherwise specified.) Bars A to T are shown in Figure 1.

The juxtaposition of Holocene terraces, streamside bedrock outcrops, and the present channel (Fig. 2; map by Watson, 1985) suggests how the present planform of Jacoby Creek has evolved. A series of Holocene terraces lies opposite bedrock bends, the lower and younger terraces or flood plains being closest to the present channel. These terraces contain 1- to 3-m accumulations of alluvium, and the oldest terrace (T2) lies 4 to 6 m above the present channel. Lateral channel migration and more gradual valley incision have cut high bedrock cliffs against the oldest terrace or the valley walls. This suggests that the channel has remained alongside the cliffs for millenia, as the cliffs have gradually eroded outward and

Geological Society of America Bulletin, v. 97, p. 999-1011, 13 figs., 1 table, August 1986.

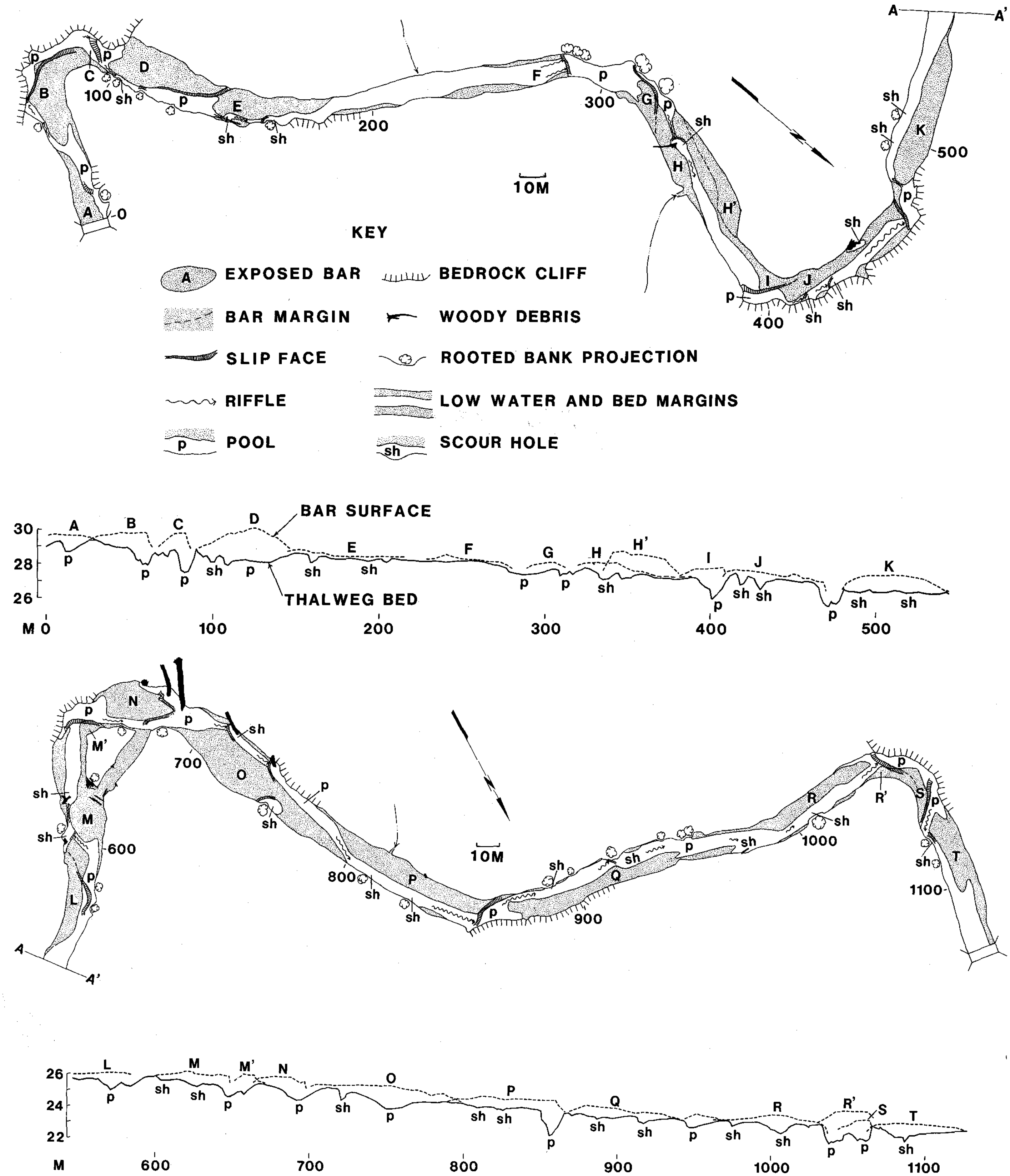



**Figure 1. Plane-table map of the lower 1,150 m of the study reach and longitudinal profiles of the thalweg and bars, Jacoby Creek, California. Map and profiles were surveyed in summer 1982. Bars are labeled from A to T downstream.**

flood plains and terraces have formed on the opposite side of the channel. As a result, meanders that are cut along bedrock outcrops have increased in amplitude but have migrated neither downstream nor back and forth across the valley.

## METHODS

A planimetric map of the lower 1.2 km of the study reach (Fig. 1) was constructed using plane table and alidade. This map was used to investigate the spatial relations between bars and obstructions and bends, to measure the area of individual bars, and to measure the width of obstructions.

A longitudinal profile of the water surface, thalweg bed, and mean bar elevation in the entire reach was surveyed using a level at low, steady flow (0.03 $m^3/s$). During this survey, water-surface elevation was no more than 0.1 m above the thalweg-bed elevation, except over pools and scour holes. The local height of bars was measured as the difference between water-surface elevation and mean bar elevation. Bar volumes were computed by summing the products of bar area and bar height measured in unit reaches one channel-bed-width long (12 m). Profiles of the thalweg bed and bars are shown in Figure 1.

A stream-gaging station was established at the downstream end of the study reach, and bedload transport was measured from the nearby bridge using a Helley-Smith bedload sampler. Using the sampling scheme of Emmett (1980), bedload transport was measured at intervals of ~ 1 hr for the duration of 4 flow events lasting 24 to 46 hr. Peak discharge for the largest two of these events was approximately bankfull. Total bedload transport was computed by integrating transport rate over time. Because of expected large temporal variations in bedload transport, total transport volumes are intended only for order-of-magnitude comparisons.

The study reach was inspected after each large flow event to observe channel changes. In addition, 3 to 4 cross sections over bars D, M, Q, and T (Fig. 1) were surveyed 5 to 10 times during the 4-yr study period. Volumes of scour and fill of these bars were computed by multiplying bar area by the average depth of scour and fill measured from surveys before and after 7 flow events that had peak discharges from 1.9 to 8.8 times the threshold discharge for transport of the median particle size of the bed surface ($D_{50}$).

To measure maximum depth of scour, scour chains (lengths of small chain inserted vertically into the streambed, after Leopold and others, 1964, p. 235) were inserted at 0.6-m intervals at 2 cross sections at the upstream ends of bars D and T. Chains were exhumed and measured after 1-yr intervals twice during the study period.

## OBSERVATIONS OF THE EFFECTS OF OBSTRUCTIONS AND BENDS ON BAR-POOL TOPOGRAPHY

Obstructions and bedrock bends in Jacoby Creek individually disrupt uniform flow patterns to cause local scour and deposition. As a series of large, stable, structural features, they also appear to control the location of pools and bars and to limit channel changes. These observations are described in the following section.

### Bed Topography and Water-Surface Configuration

**Bed Topography.** Typical obstruction-related bed morphologies have been formed around a large bedrock outcrop (Fig. 3A) and a smaller, stump-lined bank projection (Fig. 4). A deep scour hole which is surrounded upstream by a steep slip face has formed at each of the obstructions. The bed is scoured deepest just downstream of the farther projection of the obstruction into the channel. Farther downstream, the scour hole gradually shoals and widens.

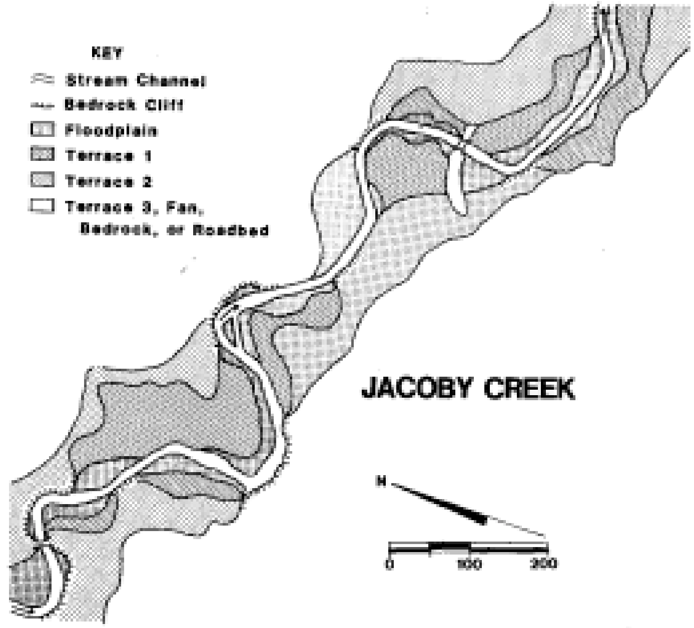
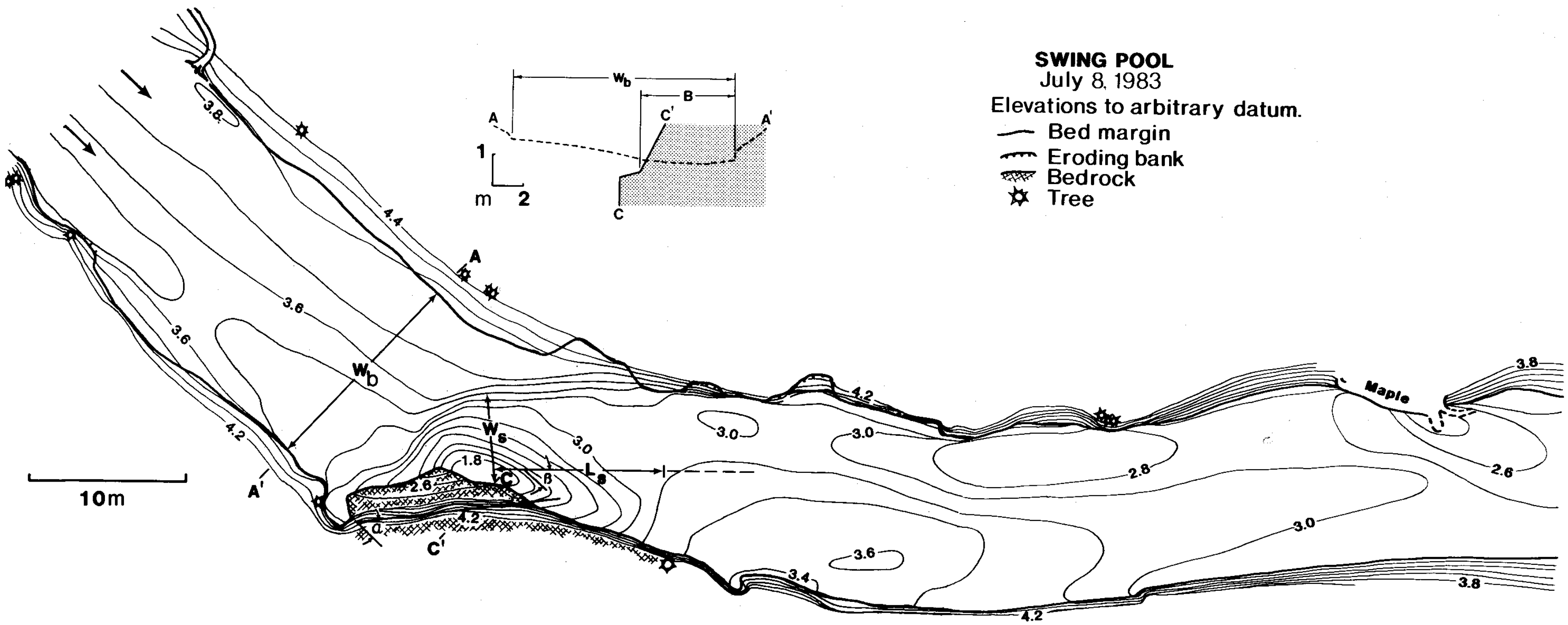



**Figure 2. Flood-plain and Quaternary terraces along a portion of the study reach, Jacoby Creek, California (mapped by C. Watson, 1985).**

These examples also show an important difference in the relative effects of large and small obstructions on channel morphology. The scour hole of the larger obstruction extends across the entire channel and thus forms the terminus of the upstream bar; another bar is formed downstream of the scour hole on the obstruction-side bank. In contrast, the scour hole of the smaller obstruction is surrounded by a single bar.

**Water-Surface Expression of Flow Structure**. Figure 3B shows the water-surface configuration in and around Swing Pool during a bankfull flow. The nearly uniform flow approaching the large bedrock outcrop was greatly disrupted by the outcrop. Surface stream lines approaching the outcrop intersected a strong eddy line nearly parallel to the outcrop, downwelled along the eddy line, and rose to the surface along both banks. Turbulent boils rose to the surface between the eddy line and the outcrop. On the opposite side of the channel, a large coherent vortex apparently forced flow along the bottom toward the inside bank. The axis of this vortex was aligned presumably over the pool deep nearly parallel to the outcrop. The eddy line was most turbulent and unstable at its downstream-most junction with the approaching stream lines. Farther downstream, the eddy line broke up and boils appeared across the channel, as the major vortex dissipated. The boils weakened downstream and were advected at increasing velocities.

Superelevation of the water surface against obstructions in Jacoby Creek has caused some high transverse water-surface gradients. Maximum transverse gradient in Swing Pool equaled 0.5% at a discharge of 9.3 $m^3/s$, and maximum transverse gradient in the upstream-most pool in the mapped portion of the study reach equaled 3% at a discharge of 42.0 $m^3/s$.



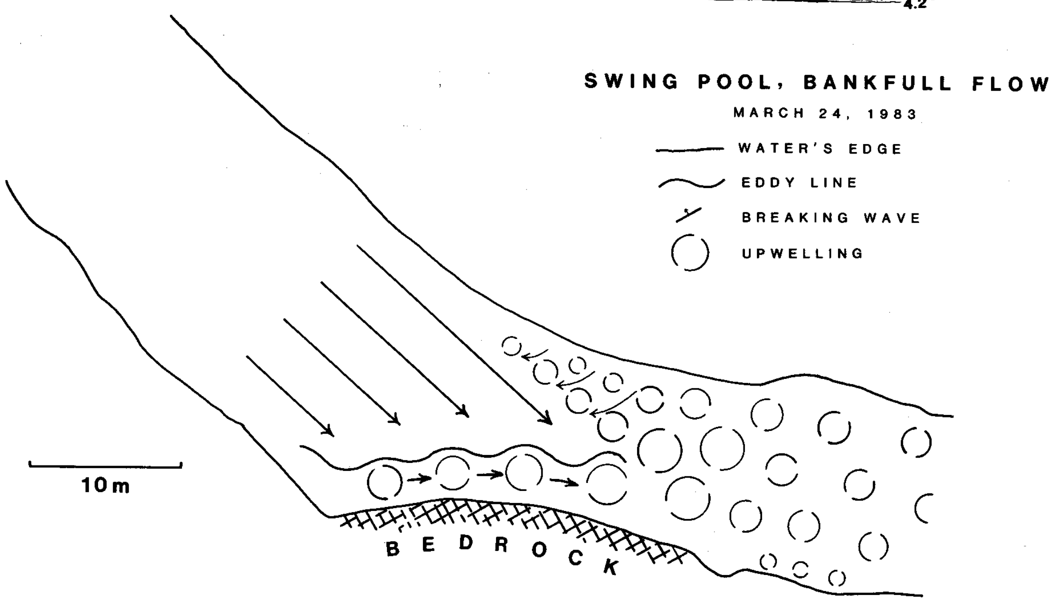




**Figure 3.** Swing Pool, scoured around a large bedrock outcrop at 8 + 70 m, Jacoby Creek, California. A. Channel topography. B. Water-surface features at bankfull flow.

Because these gradients are approximately equal to or greater than the longitudinal gradient, they can be expected to generate strong secondary circulation which directs bottom velocities away from the obstructions.

Scour is clearly associated with intense, large-scale circulation created around the outcrop in Swing Pool, and deposition occurs where secondary currents dissipate and the flow becomes more uniform. A more detailed description of sediment transport around obstructions as observed in laboratory experiments is given in a later section.

**Pool Formation by Obstructions and Bends**

Most pools in Jacoby Creek are closely associated with bedrock bends and large obstructions. Of a total of 39 pools extending across the entire channel in the study reach, 33 (85%) were in bends or next to large obstructions. (A "large obstruction" is defined here as one obstructing more than one-third of the approaching channel width, after an empirical criterion to be presented later.) The remaining pools were formed at distributary junctions or along large diagonal bars. These bars, for example, bar D downstream of a bedrock bend (Fig. l ),constricted the thalweg channel and caused scour along the opposite bank. Three of 36 bends or large obstructions (8%) did not form pools. In each of these cases, bends or large obstructions were closely spaced (less than two channel-widths apart), or a large obstruction was high on a bar surface.

**Bar Formation Around Obstructions and Bends**

The mapped reach (Fig. 1) shows evidence for bar formation upstream and downstream of large obstructions and bends. Low bars having indefinite upstream origins and terminating at slip faces (for example, bars F, L, and R) are formed upstream of some bends and large obstructions. Such bars may also merge into point bars (for example, I, M' and R'). Large diagonal bars commonly form downstream of large obstructions on the obstruction side of the channel or downstream of bedrock bends along the outside bank (for example, bars D, K, N, Q, T). These bars that are higher along one bank apparently force the flow toward the opposite bank and thereby help to erode a thalweg course along that bank. The thalweg crosses over the upstream end of these bars to the opposite bank where scour holes (commonly) and pools (rarely) form along root-defended bank projections and large woody debris. The thalweg commonly extends with little sinuosity from one pool formed around a bend or large obstruction to the next.

Bars that are most clearly associated with individual bends or large obstructions are in consistent cross-channel positions. There were 18 locations in the study reach where bends or large obstructions were separated by distances of >5 channel-widths. At each location, the upstream bend or large obstruction should determine the location of the intervening bar. In all 18 cases, a diagonal bar was formed downstream along the obstruction-side bank or outside bank of a bend.

**Correlation of Bar Volume and Bank Projection Width.** To test objectively whether bars are formed in the vicinity of bends and obstructions, statistical cross-correlation techniques were used (Kendall, 1976; Richards, 1976). Bar volume and bank-projection width were measured in 104 unit reaches 12 m (1 bed-width) long in the lower 1.2 km of the study reach (Fig. 5). Measuring bank-projection width at regular intervals removed possible bias in measurement. In the method used, a bend was marked by a series of high values of bank-projection width. The downstream series of values of bar volume was cross-correlated with that of bank-projection width at fixed distances (lags) from where bar volume was measured. Bar volume and projection width were also auto-correlated to test if they were regularly repeating features, a sign of being created predominantly by alluvial processes (Richards, 1976).

Correlation coefficients were calculated for lags of from 1 to 24 bed-widths. In analyzing cross-correlations of bar volume with bank projections, 24 lags extending both upstream and downstream were tested. Not having a geomorphic basis for choosing a confidence interval, I chose the 5% level to test individually whether each correlation coefficient was zero. Another confidence interval was determined using the Bonferroni adjustment to achieve an over-all type 1 error rate of, at most, 5% (Miller, 1981). The Bonferroni adjustment compensates for the increasing probability of finding a significant correlation in cases in which a greater number of lags are tested.

Bar volume and bank projections measured in 104 contiguous unit reaches were distributed unequally throughout the study reach (Fig. 6). Spatial correlation between these variables is not obvious, although some reaches that have high bar volumes also contained wide bank projections, for example, unit reaches 3 to 14. Time series analysis failed to yield coefficients of auto-correlation of bank-projection width that are significantly different from zero at a 95% confidence interval (Fig. 7A), indicating that obstructions and bends are spaced irregularly

Bar volume and projection width were significantly cross-correlated at the 5% level at lags of -1, 3, and 4, indicating that bars tend to form 1 bed-width upstream and 3 to 4 bed-widths downstream of bends or large obstructions. None of these lags, however, yielded significant cross

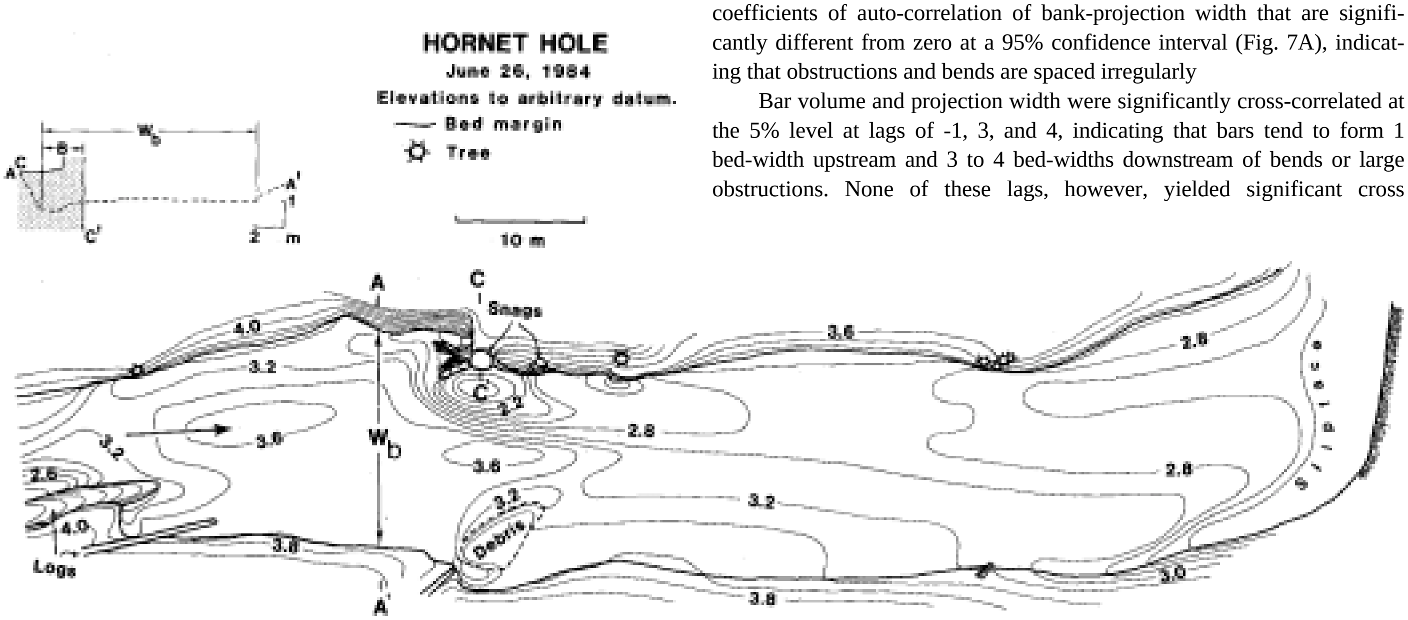



**Figure 4. Channel topography near Hornet Hole, scoured around a root-defended bank projection 0.7 km upstream of the reach depicted in Figure 1.**

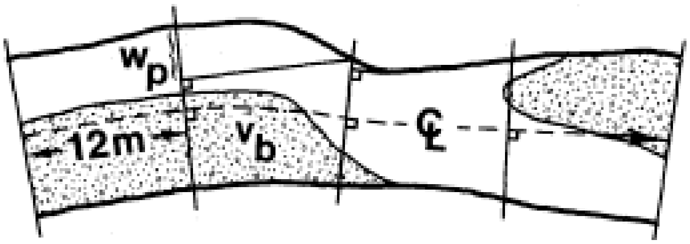



**Figure 5. Example of four channel parcels one channel-bed width (12 m) long used to measure incremental bank projection width *(*$w_p$*)* and bar volume *(*$v_b$*)* in the lower study reach. Channel margins along each parcel are projected normal to the upstream parcel boundary to measure the width of bank projections. Bar volumes in each parcel are the product of bar area and bar height above the low-water surface elevation measured from longitudinal profiles (Fig. 1).**

correlation with the Bonferroni adjustment for type 1 error (Fig. 7B). Correlation coefficients equaled 0.22 (standard error = 0.098), 0.23 (s.e. = 0.100), and 0.28 (s.e. = 0.100), respectively.

**Bar Length and Spacing**

Large obstructions and bends in Jacoby Creek create the downstream terminus of bars by causing scour across the entire channel width. Bars are terminated upstream or directly opposite the largest obstructions or in the upstream limbs of bends (for example, bars B, C, J, M, P, and R, Fig. 1). At smaller obstructions (for example, bars A, L, O, and Q), the upstream bar can extend downstream of the obstruction, where it is intersected by the pool or the bed configuration generated downstream of the pool.

The spacing of bends and large obstructions apparently controls the length of many bars. Bar length does not appear to be proportional to bar height; there are short, high bars (C and N) and long, low ones (E, F, and H). Instead, adjacent bars tend to be of similar height regardless of length (for example, bars B-D, E-F, G-H, M-N). Bends and large obstructions more closely spaced than the unconstrained length of bars (several channel-widths) cause bars to be short (for example, bar N). Short bar-pool sequences also are formed within bedrock bends of >90° deflection (for example, bars C and S). The sequence of bars and pools is not always continuous, however. In cases in which bends or large obstructions are widely spaced (for example, 16 to 18 channel-widths between 100 and 290 m), bars may simply attenuate without terminating in a slip face (for example, bars E and H).

In part because of the haphazard distribution of bends and obstructions terminating bars, bar length measured in channel-widths is highly variable (Fig. 8). Many of the bars in Jacoby Creek are < 4 channel-widths long, although modal and mean values of bar length correspond closely to the range of bar spacing commonly found in alluvial channels (5 to 7 widths, Leopold and others, 1964).

**Stability of Bars**

Bars in Jacoby Creek appear to be in dynamic equilibrium with bedload transport and the stable bends and large obstructions that give them their form, position, and relative volume. Four years of observation yielded few instances of instability in thalweg course. Repeated surveys of cross sections over bars D, M, Q, and T (Fig. 9) showed that the over-all symmetry and bank positions of these bars did not change. No important changes were observed in other bars in the study reach without movement of large woody debris or changes in the angle at which the thalweg approaches an obstruction. In cases in which changes occurred, the thalweg usually switched from impinging against one obstruction to another.

The following example illustrates how pool position and thalweg course can change in the presence of large stable obstructions. Deformation of a transverse bar upstream of a bedrock obstruction caused the thalweg to move from one side of the channel to the opposite side (Fig. 10). As a result, the angle of attack of the flow against the obstruction was reduced from 60° to 40°, and the width of the obstruction confronting the flow from upstream was reduced from approximately three-fourths to one-fourth of the width of the upstream channel. Because the effectiveness of the obstruction to cause scour was thereby reduced, the formerly deep pool next to the obstruction filled. Given the reduced deflection of the flow by the obstruction, the downstream thalweg shifted from the right bank (aligned with the upstream face of the obstruction) to the left bank. More recently, the original thalweg course along the right bank upstream of the obstruction dominated, and a pool scoured again against the obstruction.

**Potential Bar Instability.** A possible cause for bar stability during the 4-yr study period could be low rates of sediment transport. To assess the effect of sediment transport on bar instability, the volumes of individual bars were compared with the volumes of material mobilized from bars and transported as bedload during floods. A reasonable potential for gross change in bar form or position would exist if (1) bedload volumes during single stormflows were equal to most (>50%) of the volumes of individual bars, (2) the volumes of mobilized material on individual bars were equal to most (>50%) of the bedload transported during individual stormflows, or (3) volumes of material mobilized on individual bars were a substantial proportion (>10%) of the total volume of individual bars.

Volumes of bedload transported during four single stormflow events were of the same order of magnitude (14% to 113%) as that of bar volume (Table 1), meeting the first criterion above. If bedload was transported

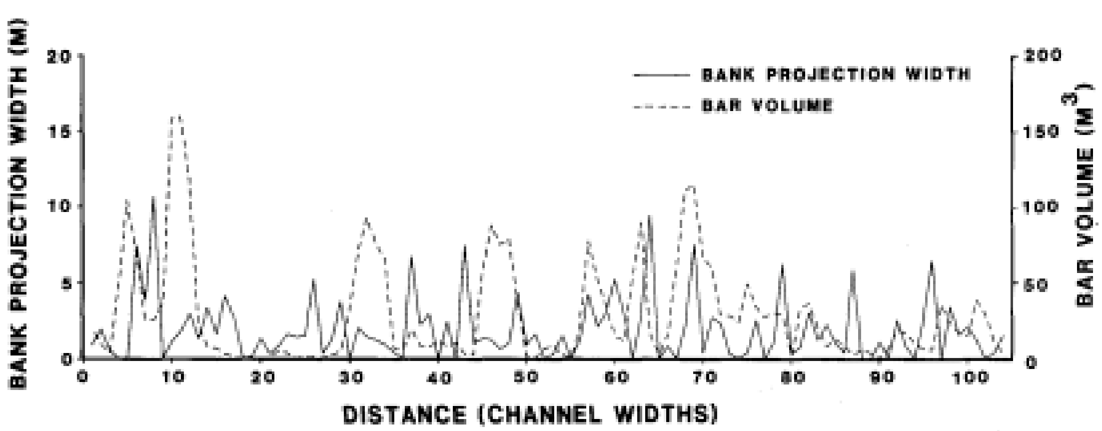



**Figure 6. Incremental bank-projection width and bar volume versus distance in channel-bed widths (12 m) in the lower study reach, Jacoby Creek, California (Fig. 1).**

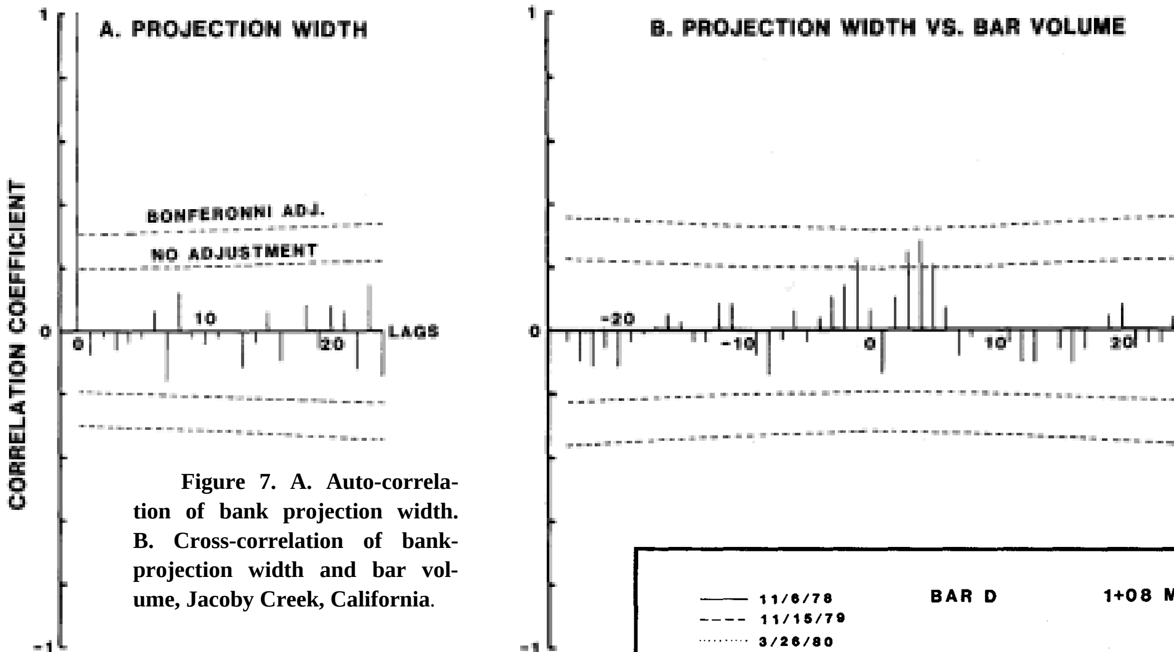



**Figure 7. A. Auto-correlation of bank projection width. B. Cross-correlation of bank-projection width and bar volume, Jacoby Creek, California.**

from one bar to the next downstream during stormflows, enough bedload would be transported to result in reworking of a substantial proportion of the volume of individual bars.

The mobilization of sediment stored in bars accounted for a large proportion of total bedload transported during sampled storms. The mean depth of scour and fill over a bar surface provides an estimate of the volume of material mobilized during sediment transport, assuming that bedload is transported from bar to bar during each flood. The exact amount passing a point downstream of a bar equals the net scour or fill of the bar plus the amount passing over the bar. The total volume of scour and fill of individual bars (18.3 to 88.2 $m^3$) was 17% to 100% of the volume of bedload (36 to 110 $m^3$) transported during 4 floods (Table 1). (Peak discharges for these floods ranged from 2.6 to 3.7 times the transport threshold for $D_{50}$.) For example, scour-fill volume of bar T lying directly upstream of the bridge from which bedload transport was measured ranged from 17% to 61% of total transport for 3 flow events.

The depth of scour in excess of that measured by repeated cross-section surveys was measured using scour chains for two 1-yr intervals at bars D and T. Excess scour volume was of the same order of magnitude as that of the scour-fill volume measured by cross-section surveys between storms (Table 1). Taking this into account, the total volume of material mobilized from individual bars during floods could commonly equal the total volume of bedload transported during those floods.

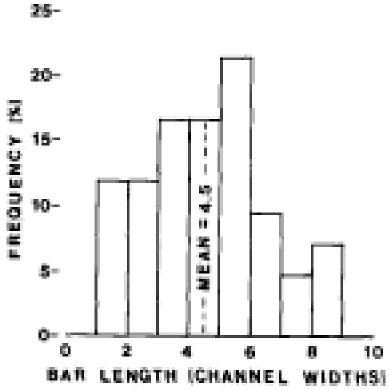



**Figure 8. Frequency of the lengths of 42 bars measured in channel-bed widths (12 m), Jacoby Creek.**

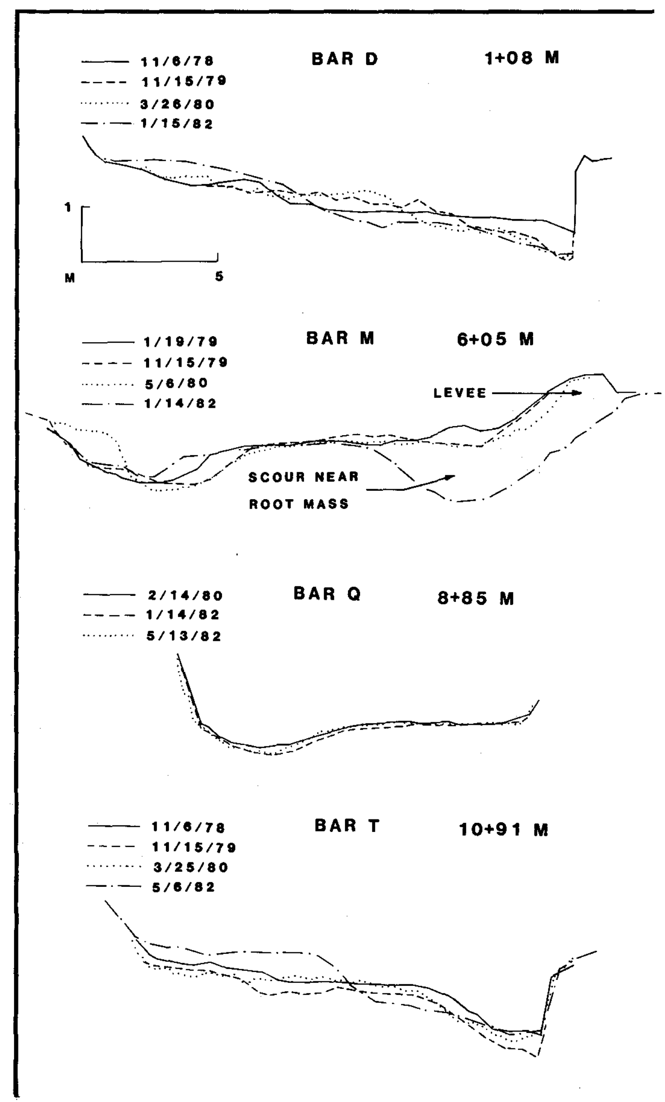



**Figure 9. Cross sections over four bars in Jacoby Creek, California, resurveyed from 1978 to 1982. A large root mass deposited on bar M in 1982 caused local scour near cross section 6 + 05 m.**

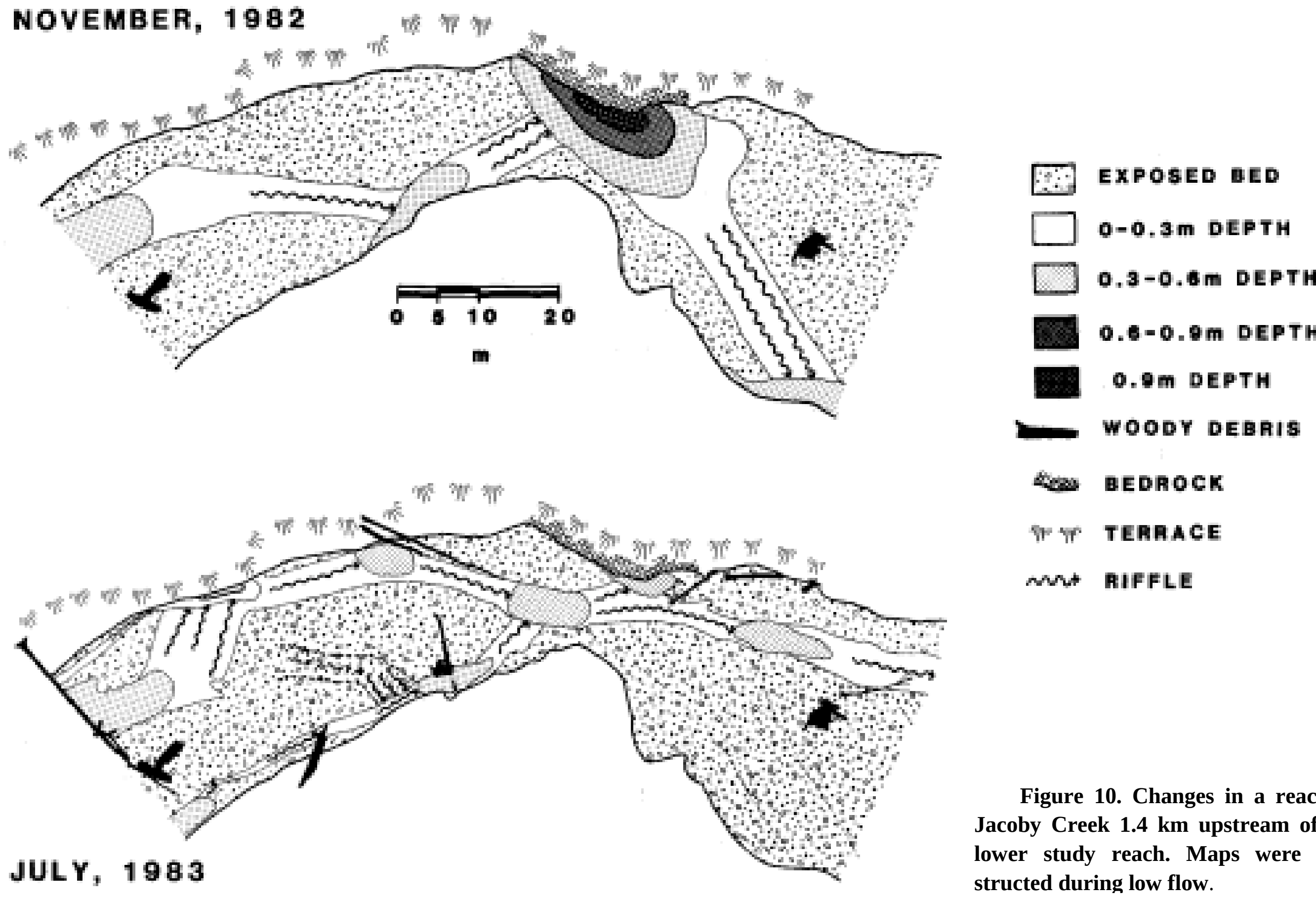



**Figure 10. Changes in a reach of Jacoby Creek 1.4 km upstream of the lower study reach. Maps were constructed during low flow.**

Finally, volumes of scour or fill relative to total bar volume (Table 1) also suggest that one or more floods have the potential to cause important changes in the form, volume, and position of bars. The percent volume of bars scoured or filled as the result of single floods averaged 25.4% (s.d. = 19.6) and ranged from 9% to 90%, depending on flow event and bar volume.

TABLE 1. VOLUME OF BED LOAD TRANSPORTED FROM STUDY REACH AND VOLUME OF MATERIAL SCOURED AND FILLED AT FOUR BARS DURING EIGHT FLOW EVENTS IN JACOBY CREEK

| Flow event | Magnitude ($Q/Q_c$)* | Bed-load volume ($m^3$)† | Scour-fill volume ($m^3$) from bar D | M | Q | T |
|---|---|---|---|---|---|---|
| 1/10-12/79 | 2.2 | 40,2 | .. | .. | .. | .. |
| 2/12-14/79 | 2.2 | 110.7 | 23.5 | 31.2 | .. | 18.3 |
| 4/10-11/79 | 3.1 | 75.1 | 37.0 | 37.6 | .. | 24.7 |
| 10/25-26/79 | 2.8 | 36.7 | 36.6 | 28.6 | .. | 22.3 |
| 3/14-15/80 | 3.9 | .. | 52.1 | 53.4 | 26.3 | 55.3 |
| 4/20-21/80 | 1.6 | .. | .. | .. | 24.0 | .. |
| 12/18-20/81 | 7.3 | .. | 41.1 | 56.2<br>105.3§ | | 88.2 |
| 2/21/82 | 2.6 | .. | .. | .. | 28.1 | .. |
| Volume of scour below lowest bed elevation surveyed between floods** | | | 50.2 | .. | .. | 11.6 |
| Bar volume ($m^3$) | | | 261 | 199 | 121 | 98 |

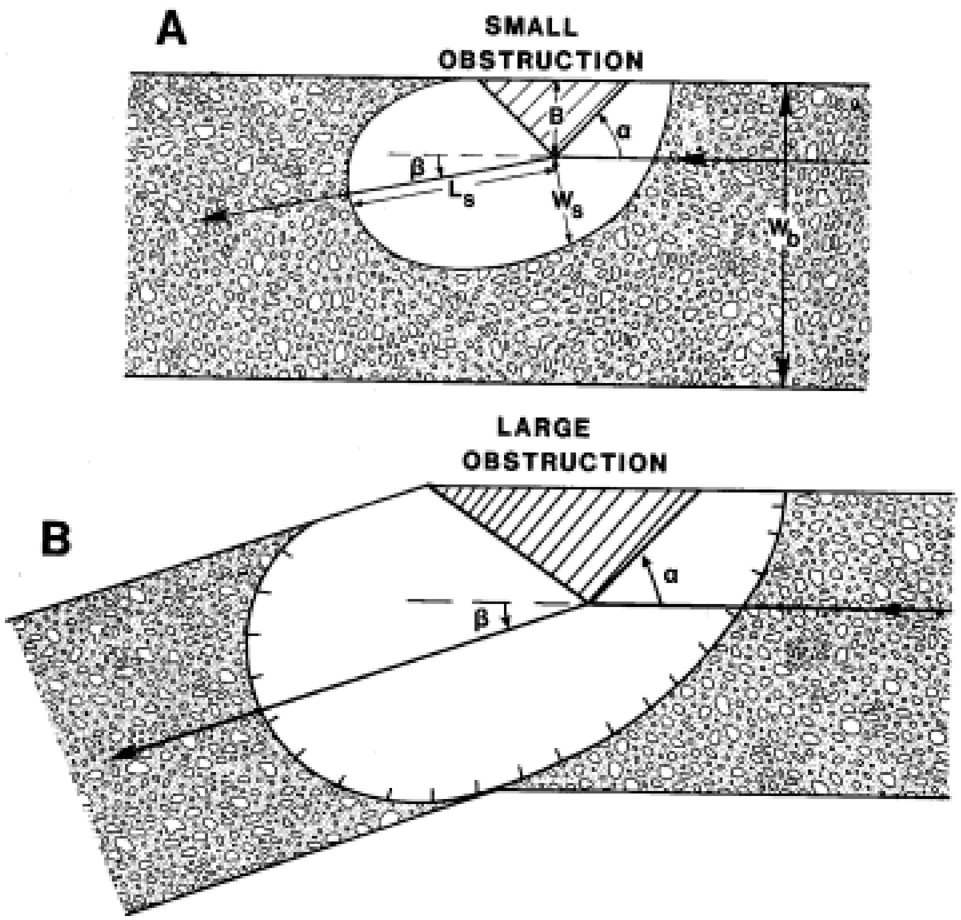
*Note*: bars D, M, Q, and T are those in Figure 1.
*$Q_c$ = 7.1 $m^3$/s, the average discharge for initial and final entrainment of gravel.
†Including porosity approximated at 0.30.
§Including scour around redwood root mass.
**Measured with scour chains at two cross sections on each bar.

## A GENERAL MODEL FOR THE STABILIZATION OF CHANNELS BY OBSTRUCTIONS AND BENDS

Control of bar-pool topography by large obstructions and bedrock bends in Jacoby Creek appeared in three ways. (1) Most pools were formed next to large obstructions or in bends; (2) bars were formed upstream and downstream of obstructions and bends at predictable locations across the channel; and (3) in the presence of frequent, erosionally resistant obstructions and bends, the channel was stable. In this section, a general model for the stabilization of channels by large obstructions and non-alluvial bends is proposed. The model was calibrated using data from Jacoby Creek in order to determine the minimum size of obstruction necessary for the proposed mechanism to operate.

### Definitions

An *obstruction* is defined as a body of material lying across a portion, but not all, of the channel projected from immediately upstream (Figs. 11A and 11B). (This paper is primarily concerned with those obstructions projecting from a bank.) If an obstruction has a planar upstream face, the angle made with the approaching channel center line (*approach angle*) will be less than the angle made between the approaching channel center line and the axis of the scour hole (*deflection angle*). A *small* obstruction forms a scour *hole* which does not extend across the entire channel bed (Fig. 11A); a *large* obstruction forms a pool which does extend across the bed (Fig. 11B). A non-alluvial *bend* has an obstructing bank lying across



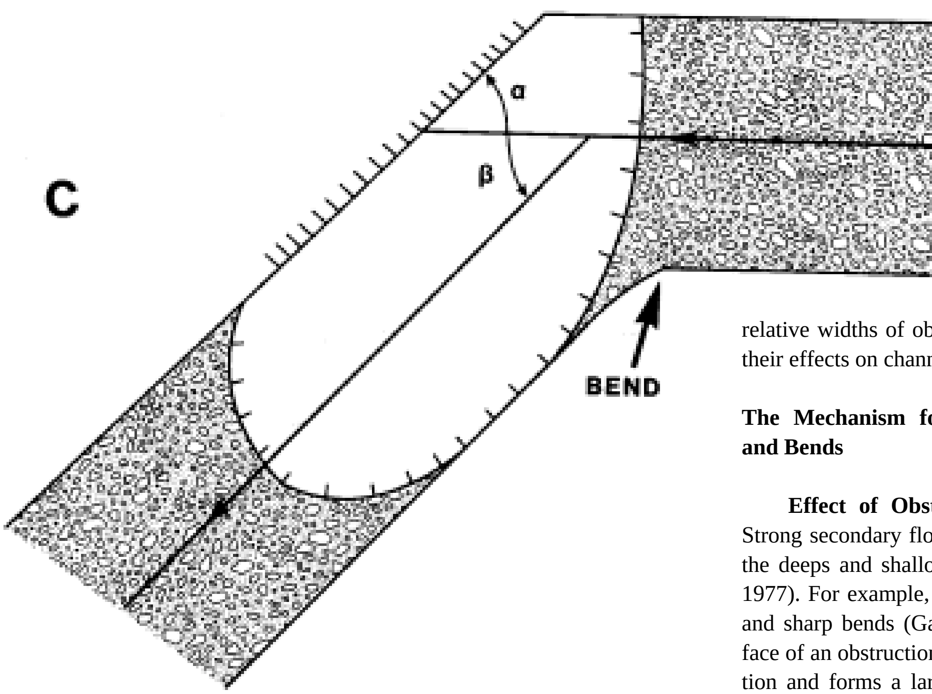




**Figure 11. Dimensions of obstructions, scoured areas, and contiguous channels for (A) a small obstruction, (B) a large obstruction, and (C) a bend. *B* = obstruction width projected normal to the approaching flow, $W_S$ = scour width measured from the obstruction to the lip of the scour hole, $L_S$ = scour length measured from the widest point of the obstruction to the downstream lip of the scour hole, α = angle between the upstream face of the obstruction and the approaching flow direction, β = angle between the axis of the scour hole and the approaching flow direction, and $W_b$ = bed width of the approach channel. It is assumed that the width of the downstream end of the scour hole, relative to the axis of the scour hole (line $L_S$), is $W_S$.**

the entire projected width of the approaching channel (Fig. 11C). If the obstructing bank of a bend is straight, then the deflection angle will approximately equal the approach angle. The progression from small obstruction to large obstruction to non-alluvial bend is a continuum in the relative widths of obstructing banks, but with well-defined limits marking their effects on channels.

## The Mechanism for Channel Stabilization by Large Obstructions and Bends

**Effect of Obstructions on Bedload Transport and Deposition**. Strong secondary flows induced around obstructions and bends accentuate the deeps and shallows inherent in mobile beds (Callander, 1969; Yalin, 1977). For example, local scour is commonly deepest around obstructions and sharp bends (Galay and others, in press). Flow against the upstream face of an obstruction produces high velocities near the base of the obstruction and forms a large, intense, persistent vortex which has a horizontal axis (Moore and Masch, 1965; Melville, 1975). This high-energy flow structure scours the bed and deflects bedload particles across the channel away from the obstruction (Schneider, 1968; Melville, 1975). The vortex and associated secondary currents generated by transverse pressure gradients are thus capable of radically altering sediment transport patterns. As a result, the channel downstream of an obstruction retains little of the pattern upstream of the obstruction.

Decreasing velocity and water-surface gradient upstream of a large obstruction can cause bedload to deposit upstream. A deposit can form downstream because flow energy is expended around the obstruction and because downstream of the obstruction, the flow expands after being constricted by the obstruction. In a theoretical explanation for channel morphology in a reach containing an obstruction or sharp bend, Gallinatti (1984) predicted that a deposit which formed downstream of an obstruction would be largest along the obstruction side of the channel. This prediction was borne out at all of 18 sites in Jacoby Creek.

**Stabilization of Bars.** Downstream-migrating bars commonly form in channels without bends or large obstructions (Collinson, 1970; Lewin, 1976; Hein and Walker, 1977; Kinoshita and Miwa, 1974; Leopold, 1982) and where bedload transport causes extensive bank erosion (Ferguson and Werrity, 1983). In such channels, bedload particles advancing over the stoss side of a migrating bar commonly avalanche down a slip face lying obliquely across their path and enter a pool (Bluck, 1976; Ashmore, 1982; Crowley, 1983; Cant, 1978). The particles are then deflected by flow directed roughly parallel to the slip face before diverging stream lines carry them onto the next bar (Allen, 1982). Because the flow along the base of the slip face is too weak to remove the total influx of sediment, the bar advances downstream.

According to the model presented here, a series of large obstructions or resistant bends can halt the migration of bars. The advance of the slip face of a migrating bar into a pool scoured around a large obstruction, for example, greatly increases the sediment input into the pool. Strong secondary currents generated by the obstruction, however, can continue to scour the bed as sediment avalanches into the pool. If these currents are strong enough, the slip face, marking the distal end of the bar will stop advancing and become aligned around the obstruction. Another bar will form downstream extending from the shoaling tail of the pool. The upstream and downstream ends of bars therefore can be fixed in position by the intense scour generated around a series of large obstructions or bends. Stabilization of bars would tend to stabilize the channel planform as well, and the thalweg would extend from one pool formed around an obstruction or bend to the next downstream.

### Minimum Dimensions of Obstructions Stabilizing Bars

The model proposes that a series of obstructions of some minimum size scours pools intersecting the entire bed width of the upstream channels and thereby terminates upstream bars and initiates others downstream. If an obstruction deflects the thalweg enough, the upstream channel can be intersected at some point downstream of the obstruction (Fig. 11 B).

Minimum width of an obstruction scouring a pool and thus terminating a bar may be calculated from the geometric relations shown in Figure 11A.

$$B = W_b - W_s \sec\beta - L_s \sin\beta \qquad (1)$$

where $B$ is the width of the obstruction, $W_b$ is the bed width of the approach channel, $W_s$ is the width of the scour hole measured perpendicular to the axis of the scour hole at the widest point of the obstruction, $L_s$ is the length of the scour hole measured from the widest point of the obstruction to the downstream lip of the scour hole, and $\beta$ is the deflection angle (Fig. 11 A). The terms in equation 1 constitute widths projected onto the plane of the cross section of approaching, but undisturbed, flow. The condition expressed in dimensionless terms is

$$B/W_b + (W_s/W_b)\sec\beta + (L_s/W_b)\sin\beta \leq 1. \qquad (2)$$

### Calibrating the Model

To determine the minimum size of obstruction forming a pool, the variables defined in Figure 11 A were measured at 26 natural obstructions in Jacoby Creek. These obstructions included bedrock outcrops, large woody debris, and root-defended bank projections. Obstructions were selected to be relatively simple in form, to extend above bankfull stage, to have nearly vertical sides facing the channel, and to be far enough from neighboring obstructions or bends to avoid modifications of the scour hole and approach section. Parallel cross sections intersecting the channel center line at the same distance on the cross sections were surveyed over the obstruction and in the approach channel upstream of the scour hole (Figs. 11A, 3A, and 4). Superimposing these two cross sections provided a measure of the width of the obstruction projected onto the plane of the cross section of the approach channel. Approach angle and deflection angle were measured using a compass.

The second and third terms of equation 2 can be evaluated from empirical functions of dimensionless characters of the obstruction.

$$W_s/W_b = 0.616\,(B/W_b)^{0.606} \quad [r^2 = 0.85;\ n = 11], \qquad (3)$$

$$L_s/W_b = 1.41\,(B/W_b)^{0.548} \quad [r^2 = 0.68;\ n = 14], \text{ and} \qquad (4)$$

$$\sin\beta/\sin\alpha = 1.05\,(B/W_b) - 0.0279 \quad [r^2 = 0.80;\ n = 16] \qquad (5)$$

where $\alpha$ is the approach angle. The three functions, equations 3, 4, and 5 (Figs. 12A, 12B, and 12C), are significant (t-test, $P < 0.01$) and allow the derivation of equation 2 (Fig. 12D).

According to this model, obstructions in Jacoby Creek confronting more than one-third to one-half of the approaching flow, depending on their approach angle, are large enough to terminate upstream bars. Equation 2 successfully separates all of the pools and scour holes (Fig. 12D) that were distinguished in the field.

Approach angle appears to be much less important than is obstruction width in distinguishing pools from scour holes. Function 5 is not significantly different from $\sin\beta/\sin\alpha = B/W_b$ (F-test, analysis of covariance, $P < 0.01$) (Fig. 12C); the degree that an obstruction deflects the channel relative to its upstream-face angle corresponds simply to its width relative to the bed width. According to function *5,* small obstructions cannot deflect the channel direction enough to have important effects on the second and third terms of equation 2. For obstructions deflecting the thalweg significantly, obstruction width and scour width are already large enough to intersect the approaching channel directly opposite the obstruction. If an obstruction spans the width of the approaching channel ($B/W_b = 1$), the downstream thalweg parallels the face of the obstruction, and, thus, the obstruction constitutes a bend.

### Comparison with Results of Kinoshita and Miwa

In a laboratory experiment, Kinoshita and Miwa (1974) found that sharp bends that have deflection angles of at least 10° to 30° (the minimum value depending on bend wavelength) stopped the advance of alter

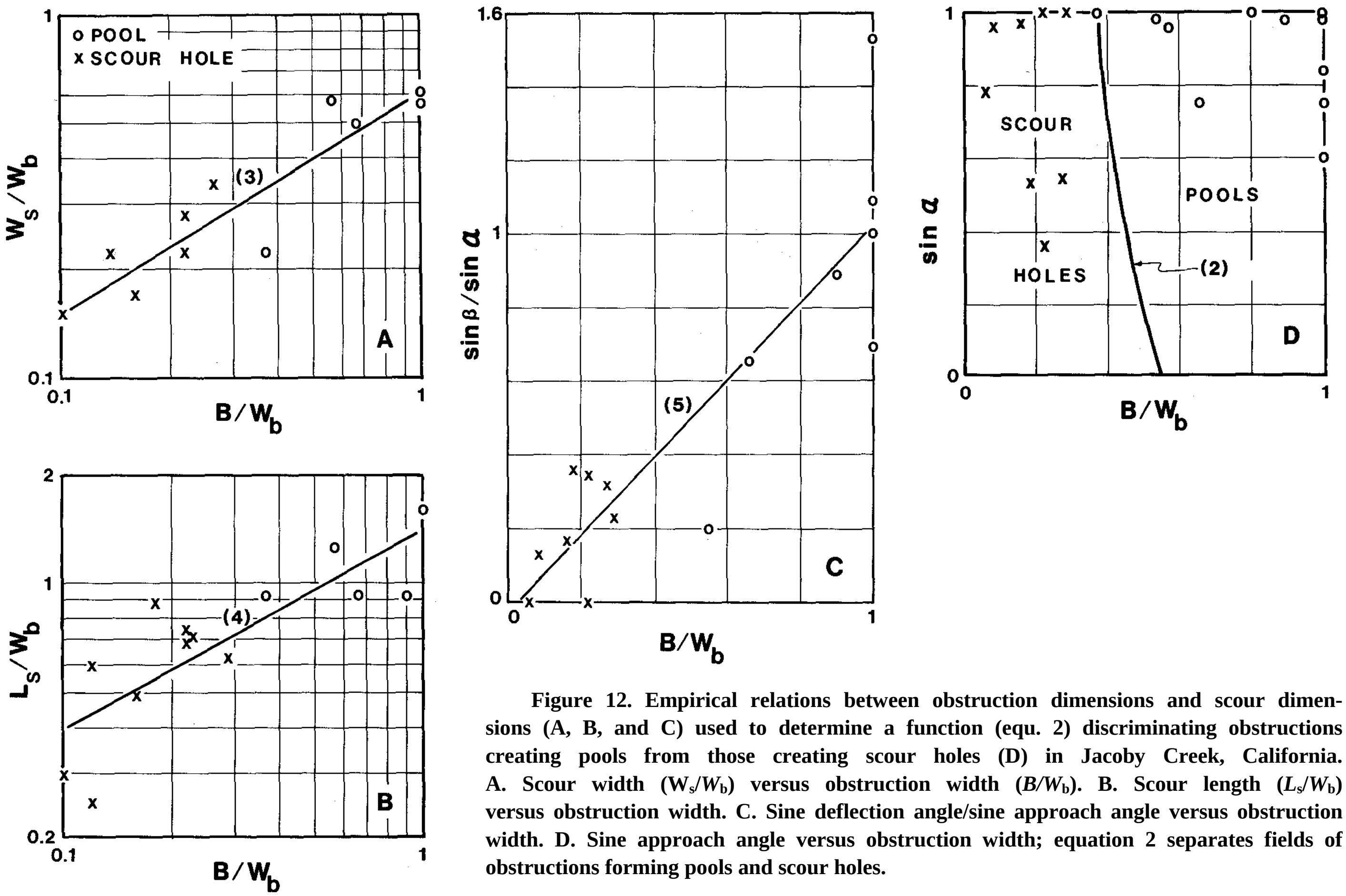



**Figure 12. Empirical relations between obstruction dimensions and scour dimensions (A, B, and C) used to determine a function (equ. 2) discriminating obstructions creating pools from those creating scour holes (D) in Jacoby Creek, California. A. Scour width ($W_s/W_b$) versus obstruction width ($B/W_b$). B. Scour length ($L_s/W_b$) versus obstruction width. C. Sine deflection angle/sine approach angle versus obstruction width. D. Sine approach angle versus obstruction width; equation 2 separates fields of obstructions forming pools and scour holes.**

nate bars. Bars continued to advance through a *single* bend regardless of deflection angle, although they slowed when the pool between migrating bars was in phase with the scour hole forming at the bend. Bars migrating through a *series* of alternate bends stopped as soon as pools between bars and scour holes at bends were in phase. By comparing sequential aerial photographs of Japanese rivers, they also found that bars were stable if bends had average deflection angles greater than ~20° and bars migrated through bends that had deflection angles <20°.

Critical geometries for terminating bars with streamside obstructions in Jacoby Creek can be compared to those for stalling migrating bars with bends in Kinoshita and Miwa's (1974) experiment (Fig. 13). In their experiment, bars in a series of bends were stabilized if a stream line extending from the inside bank of a straight channel segment intersected the opposite bank no more than two-thirds down the length of the next segment (Fig. 13A). In a straight channel which has obstructions producing an equivalent geometry, the flow impinges upon the obstructions along lines parallel to the channel margins (Fig. 13B). The two cases are equivalent if

$$B/W_b = [L/(W_b - B)]\,[\tan(\theta_c/2)]$$

where $L$ equals bend wavelength, $\theta_c$ equals the critical angle for bar stabilization, and $W_b - B$ equals the width of the straight segments between the channel bends. Given a bend frequency, $L/(W_b - B)$, of 5, relative obstruction width, $B/W_b$, equals 0.43. This value equals the approximate width of obstructions that terminate bars in Jacoby Creek. The critical stabilizing geometries of the two studies are thus apparently equivalent.

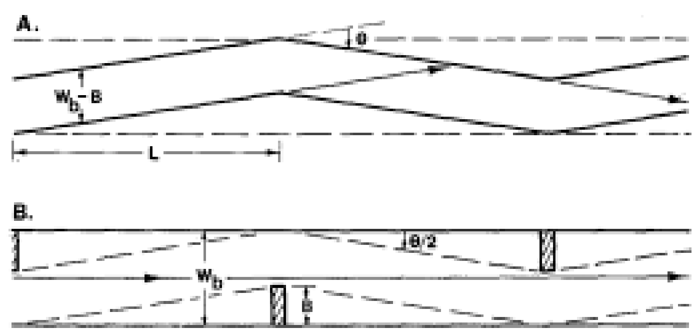



**Figure 13. Comparison of models for minimum channel geometrics stabilizing the downstream positions of bars. A. Channel with bends (after Kinoshita and Miwa, 1974). The channel is delineated by solid lines; the bend belt, by dashed lines. B. Channel with streamside obstructions at spacings equal to one-half the bend wavelength of channel A. The width of the bend belt of channel A equals $W_b$, the width of channel B between obstructions. The width of channel A at bend apices equals $W_b - B$.**

## DISCUSSION AND CONCLUSIONS

### Obstructions and Bends

Obstructions are of interest to geomorphologists because, unlike meanders, they are commonly formed or introduced predominantly by non-fluvial processes and can therefore independently affect the behavior of channels. Some non-alluvial bends may also have non-fluvial origins, but it is important to distinguish obstructions from bends in order to be able to clearly recognize independent controls on channel processes. The geometric distinctions between obstructions and bends are that obstructions (1) intersect only a portion of the width of the projected oncoming flow and (2) project from a bank, so that they deflect the flow less than the angle made between the oncoming flow and their upstream face.

Obstructions and bends are similar enough in their effects on channel form and on the pattern of flow and sediment transport, however, to suggest that they lie on a continuum of bank forms affecting channel morphology. Large-scale secondary flow structures, including the major vortex scouring a hole next to an obstruction and an oppositely circulating system next to the obstruction, have similar counterparts in alluvial meanders (Leopold and Wolman, 1960; Hickin, 1978; Hey and Thorne, 1975). The slip face which forms opposite the upstream face of an obstruction is similar in location to the point-bar slip face in a meander commonly formed opposite the bank segment immediately downstream of the minimum curvature radius (Dietrich and Smith, 1984; see also maps of Friedkin, 1945; Hooke, 1975; and Leopold and Wolman, 1960). Most importantly, the mechanism of stabilizing bar-pool topography is the same for a series of either large obstructions or bedrock bends.

### Factors Influencing Bar Stabilization by Obstructions and Bends

One prerequisite for channel control by bends or large obstructions is that they occur in sufficient frequency. In Kinoshita and Miwa's experiment, bars continued to migrate down channels that had a single bend. Similarly, in the Connecticut River, Reid (1984) observed that limbs of downstream-migrating meanders wrapped around and stalled against isolated bedrock knobs until the next limbs upstream were able to pass the knobs. He speculated that a series of alternating resistant bank segments could dampen lateral migration of the channel. Large obstructions or bends spaced at common riffle-pool frequencies of several channel-widths would perhaps exert the strongest control on bar-pool morphology.

Bends and obstructions may most effectively control the formation of diagonal and transverse bars in steep gravel channels (Florsheim,1985) in which free-stream flows with low depth:particle-size ratios inhibit bar formation (Kopaliani and Romashin, 1970; Church and Jones, 1982). Kinoshita and Miwa (1974) suggested that bends in a channel can produce "forced bars" where alternate bars would not otherwise form. Forced bars produced by bends or obstructions would be especially stable because they owe their existence to relatively stable boundaries.

### Long-Term Control of Channels by Bedrock Outcrops

Measured rates of channel migration across narrow valleys confined by bed rock are quite slow (Palmquist; 1975; Brakenridge, 1984, 1985). Terrace and flood-plain stratigraphy of the confined valley bottom of Duck River, Tennessee, indicates that gradual vertical accretion of overbank sediments is more responsible for flood-plain formation than are lateral channel migration and point-bar deposition (Brakenridge, 1984). As in the case of Jacoby Creek, series of terraces lie opposite steep bedrock outcrops forming bends, and modern alluvial deposits appear to be tied to the bedrock bends.

Bedrock obstructions and bends may possibly retard meander migration in confined valley bottoms by directly and persistently affecting channel courses. Bedrock obstructions and bends along Jacoby Creek deflect the channel to a greater or lesser degree depending on the proportion of the channel obstructed. Regardless of the degree of deflection, the downstream channel course is trained by a stable boundary configuration. In contrast, banks in alluvial meanders are smoothly curving and frequently change with erosion and thus do not set persistent directions for reaches immediately downstream.

Large obstructions and bedrock bends may also stabilize channel courses by fixing the position of bars and pools. Channel migration is more likely to occur along banks adjacent to pools, in which shear stress is high and skewed toward one bank (Hooke, 1975; Dietrich and others, 1979; Dietrich and Smith, 1984), than in riffles, which can be relatively stable (Richards, 1976; Milne, 1982; Andrews, 1982). Large pools that are formed by projections and tight turns along resistant bedrock banks are constrained from migrating. Dury (1970) and Neill (1976) found that deep pools formed against bedrock outcrops were stable for decades. Similarly, probability contours of channel locations in the Salt River, an unstable sand-bed channel in Arizona, revealed areas of preferred channel courses along buttes (Graf, 1981). Channel migration in reaches between bedrock outcrops may also be slow because these reaches are relatively straight and commonly contain riffles and because lateral erosion would be limited by the stable bar alignment produced by an upstream outcrop. The planform which has apparently resulted in Jacoby Creek is a series of nearly straight channel segments joining abrupt and irregular deflections against bed rock, large stable woody debris, and stream banks rooted by long-lived trees.

### Conclusions

Large streamside obstructions and bends that are formed of resistant material can stabilize gravel channels by controlling the location of pools and bars. This general model is supported by observations of a natural gravel-bed channel. Additional theoretical development, laboratory experiments, and field observations of other channels are needed to test the model adequately and to determine the strength of the influence of obstructions and bends given a variety of conditions. The effects of irregular, non-alluvial boundaries may have some important consequences for channel behavior and the development of flood plains and terraces.

## ACKNOWLEDGMENTS

Harvey Kelsey served as a thoughtful and critical sounding board for the ideas in this paper, suggested field methods, assisted in data collection, and encouraged me during the entire course of this research. I gratefully acknowledge his vital support. Critical reviews by Kelsey, Mike Church, Bill Dietrich, and Lori Dengler greatly improved this paper. Keith Richards suggested methods for time series analysis and performed a preliminary analysis on the longitudinal profile. Gary Parker introduced me to Kinoshita and Miwa's work and translated their paper from Japanese, Rand Eads shared bucolic days of plane-table mapping of the study reach. Kate Bean, Marcus Chamberlin, Joan Florsheim, Andre Lehre, Jed Lengyel, Judy McHugh, and Rick Smith freely assisted me in field work. I wish to thank all of these people for helping me with this research.

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MANUSCRIPT RECEIVED BY THE SOCIETY JUNE 27, 1985
REVISED MANUSCRIPT RECEIVED JANUARY 30, 1986
MANUSCRIPT ACCEPTED FEBRUARY 5, 1986