

FLUVIAL REQUIREMENTS FOR GRAVEL BAR FORMATION
IN
NORTHWESTERN CALIFORNIA

by

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ABSTRACT

The purpose of this study is to evaluate a slope threshold for bar formation, and to qualitatively analyze empirical relationships among variables which affect bar occurrence and morphology for 15 gravel bed stream reaches in northwestern California. Channel bar formation depends mainly on slope, particle size, and width to depth ratio. A model for the slope threshold above which no bars are present is contrasted with the field data for this study. Church and Jones' (1982) model based on the relation of flow depth to particle size determines the maximum slope allowable for bar formation. The slope threshold ranges between 0.025 and 0.08 when Shields' (1936) value of $\tau_* = 0.05$ is used. When Parker and Klingeman's (1982) value $\tau_* = 0.017$ (for D_{90}) is used, the slope threshold ranges from 0.003 to 0.01, and when their value $\tau_* = 0.035$ for D_{50} is used, the slope threshold ranges between 0.017 and 0.058. Based on field data for northwestern California coastal streams, no riffles or storage bars are present at slopes above 0.02 in reaches without obstacles. At slopes greater than 0.02, step-pool structure is common. Furthermore, bar morphology is dependent on the relation between slope and bed material size. Storage bars attain a height of 0.71 bankfull depth; riffles attain a height of 0.26 bankfull depth. Bars in the study reaches are present at bankfull width to depth ratios less than predicted by Jaeggi (1982) and Parker (1978). The relationship between flow intensity and the product of channel slope and

width to depth ratio, indicates distinct fields for gravel bar morphology including: storage bars with riffles, storage bars only, and no bars (with step-pool morphology). Steep north coastal reaches would probably form braid bars if mean particle sizes were smaller or width to depth ratios were larger.

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INTRODUCTION

Channel bars in gravel bed streams are sedimentary accumulations whose length is equal to or greater than the river channel width (ASCE, 1966). Bars form as a response to the interactions of stream flow moving over a mobile sediment bed.

Knowledge of the fluvial conditions required for bar formation is essential in understanding bar occurrence in natural channels. Bars form the structure of riffle-pool sequences in alluvial channels without obstacles and are storage sites for mobile sediment. Gravel bar formation is of practical importance in California's north coastal streams since bars form the natural spawning grounds for anadromous fish and create heterogeneity in hydraulic conditions required by the various species and ages of juvenile salmonids (Dury, 1955).

The purpose of this project was to determine the conditions for forming bars of various morphologies in straight natural channels with coarse bed material. Channel slope, bankfull width and depth, particle size, and bar height were measured in 15 straight reaches in the drainages of five gravel bed rivers in the north coastal region of California (Figure 1). Shear stress, critical depth, and shear velocity were calculated from the field data.

A classification for bar morphology pertinent to straight north coastal study reaches is first presented. The following sections give theoretical background of how hydraulic variables such as shear stress, channel slope, flow depth, and width to depth ratio, and grain size

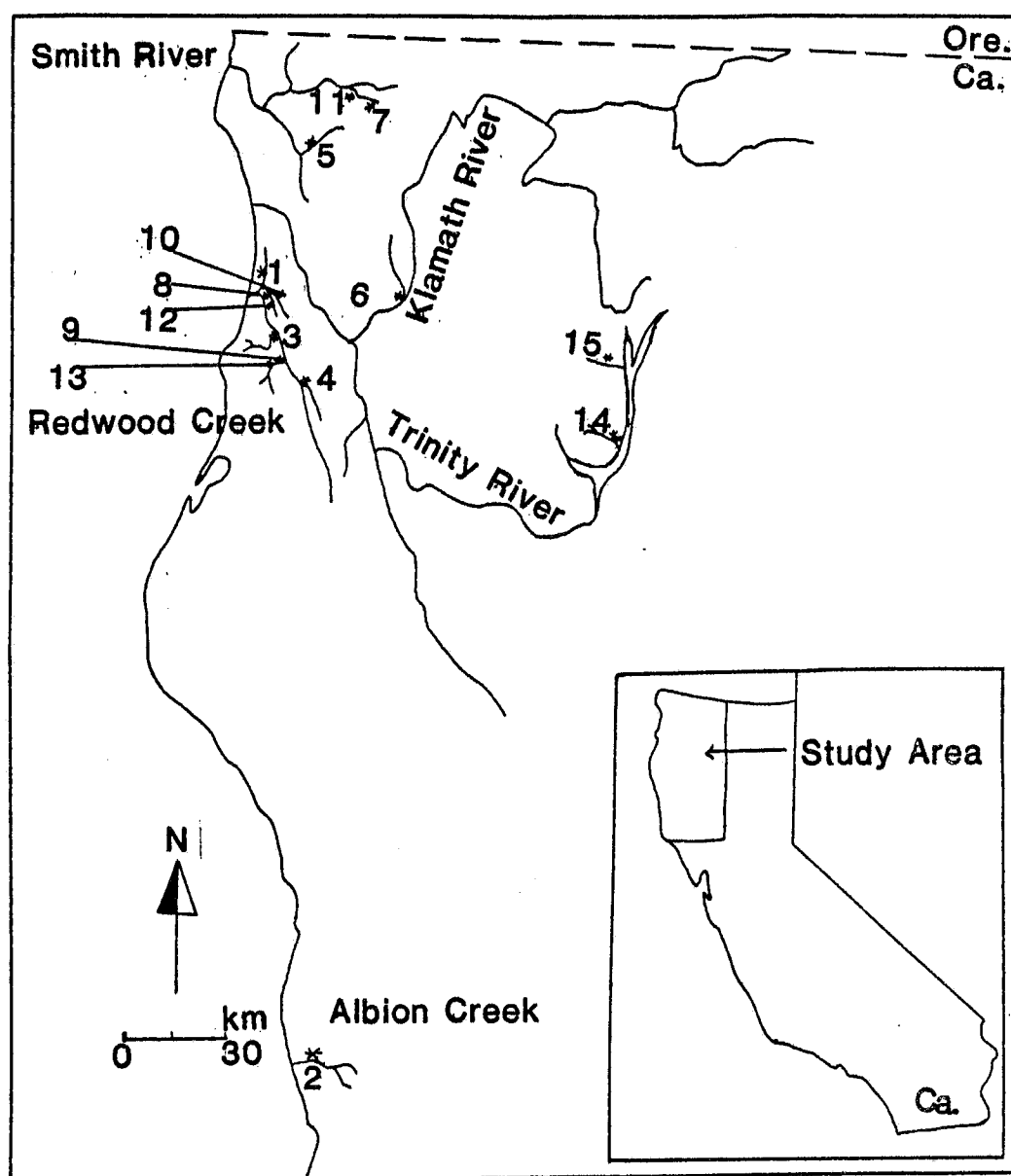


Figure 1. Location of Study Reaches in North Coastal Physiographic Province. Reach location indicated by "*". Reach 1, Prairie Creek; reach 2, Albion Creek; reach 3, Tom McDonald Creek; reach 4, Lacks Creek; reach 5, Hurdygurdy Creek; reach 6, Camp Creek; reach 7, Siskiyou @ Paranoia Farm; reach 8, Little Lost Man @ Bridge; reach 9, Bridge 11; reach 10, Little Lost Man @ Cable; reach 11, Siskiyou @ Harry's Dredge; reach 12, Little Lost Man @ Gage; reach 13, Bridge 1; reach 14, Swift Creek; reach 15, E. Stuart Fork.

affect gravel bar formation and morphology. Results are analyzed in five ways. First I determined a channel slope threshold for bar formation and morphology for the study reaches and compared this value to the threshold predicted by Church and Jones' (1982) slope threshold model. Second, I related flow depth to bar height. Finally, I analyzed three empirical relationships involving measured and calculated variables that affect bar formation in the north coastal study reaches. These three relationships are: slope vs. width to depth ratio; slope vs. mean particle size; and the product of slope and width to depth ratio vs. flow intensity.

DISCUSSION

Channel Slope

This study suggests that a slope threshold exists for gravel bar formation. Figure 5 indicates that as slope increases, the type of bar changes from riffles with storage bars and storage bars only at slopes less than 0.02, to reaches with no bars for slopes greater than 0.02. In these high gradient streams, the depth of flow at critical conditions is too small to allow for accumulation of large clasts, and a plane bed forms. Alternatively, during high magnitude events, step-pool structure can be formed by the same process which produces anti-dunes, where heterogeneity of the bed material disturbs the regularity of the step spacing. Bars could form at these high gradients if obstructions were present.

Church and Jones' (1982) Slope Threshold Model

Church and Jones (1982) suggest that a limiting value for bar forming flows can be determined by relating slope (S) to relative roughness (D_{90}/d_b), where D_{90} is measured on bars. Since sediment must be moved by traction to the highest point of a bar, sediment entrainment equations provide some limiting expressions for bar-forming flow. A maximum slope for bar formation is predicted by Church and Jones' (1982)

model as discussed in the theoretical background section. When Shields' value of $\tau_* = 0.05$ is used, the transport equation is:

$$S = 0.080(D_{90}/d_b) \quad (6)$$

For values of D_{90}/d_b of 1.0 and 0.3, the predicted maximum slope for bar formation ranges between 0.025 and 0.08. A value of τ_* can be determined using Parker and Klingeman's (1982) method for gravel bed streams. A value of D_{90}/D_{50} was averaged for each reach, and the average computed for all the study reaches equals 2.92. Using the curve of the dimensionless shear stress against the ratio of D_{90}/D_{50} for the bed pavement (Parker and Klingeman, 1982, Figure 3) $\tau_* = 0.017$ for D_{90} for my data. The transport equation becomes:

$$S = 0.0103(D_{90}/d_b) \quad (11)$$

For values of D_{90}/d_b of 1.0 and 0.3, the predicted maximum slope for bar formation ranges between 0.003 and 0.01.

Figure 8 shows the predicted range of maximum slope for bar formation using both $\tau_* = 0.017$ and $\tau_* = 0.05$. For the north coastal streams, the slope threshold is approximately 0.02 (2 percent). Above this value, no bars occur in the study reaches except those created downstream of flow obstructions (Bridge Creek I; reach 13). The threshold for my study data is slightly lower than the range predicted by Church and Jones' (1982) model using Shields' value, and it is much higher than the range predicted by the model using Parker and Klingeman's value of τ_* for D_{50} . Some variation in the values derived for the slope threshold model and that observed in the study reaches is expected, since slope, bankfull depth, and particle size for the study data are values averaged over the reach, and bar formation depends on

local values of these variables. Another factor which may affect the range for maximum slope for bar formation is the apparent arbitrary nature of Church and Jones' choice of D_{90}/d_b chosen to determine the maximum slope for bar formation.

A value of 0.02 (the slope threshold for bar formation observed in my study reaches) can be used in the transport equation to derive a limit value of D_{90}/d_b corresponding to my study data. Using the transport equation with Shields' (1936) value of $\tau_* = 0.050$, a value of $D_{90}/d_b = 0.25$ is computed for the slope threshold of 0.02. Parker and Klingeman's (1982) value of $\tau_* = 0.017$ derived for D_{90} in a gravel pavement theoretically is a better value than Shields' value $\tau_* = 0.05$ (derived for spherical sand grains of uniform size). However, using the transport equation with $\tau_* = 0.017$, a value of $D_{90}/d_b = 1.94$ is computed for the slope threshold of 0.02. This is not possible conceptually, since transport of D_{90} cannot occur when D_{90}/d_b is greater than one (Church and Jones, 1982). It appears that $\tau_* = 0.017$ for D_{90} is too low a value. D_{90}/D_{50} varies widely within a reach. Averaging these local values within each reach, and averaging all 15 study reaches together may not be valid. This probably accounts for the unfeasible upper limit for D_{90}/d_b when Parker and Klingeman's (1982) method for determining τ_* for D_{90} is used.

The theoretical transport lines using $\tau_* = 0.017$ and $\tau_* = 0.050$ show the flow condition (D_{90}/d_b) necessary for entrainment of the maximum grain size (Figure 8). Transport of D_{90} is absent above the line, while transport of D_{90} occurs below the line. All the study reaches fall below the transport line derived using $\tau_* = 0.017$, while

data plots on both sides of the line derived using $\tau_*=0.05$. Assuming $\tau_*=0.017$ derived using Parker and Klingeman's method (though probably too low) is more accurate than $\tau_*=0.05$ for the limit of transport, all grain sizes are transported at bankfull stage (Figure 8).

Since entrainment sets the lower limit of bar formation, bars will not form if a reach falls above the theoretical transport line. For gentle slopes, entrainment requires large bankfull depth yielding small D_s/d_b values. Conversely, bankfull depth need be less for entrainment of D_s if the slope is steeper. Although entrainment is a necessary mechanism for bar formation, entrainment does not imply that bars will form. Reaches such as Stuart Fork (reach 15), Swift Creek (reach 14), Little Lost Man @ Gage (reach 12), and Hurdygurdy Creek (reach 5) transport sediment but do not form bars because the particle size is too large relative to the flow depth to pile particles upon each other.

As further test of Church and Jones' (1982) slope threshold model, identical analysis to that described above can be done for the mean particle size (D_{50}), where Shield's value of $\tau_*=0.05$. Assuming that $D_{50}=0.3(D_{90})$, the upper limit of D_{50}/d_b ranges from 0.1 to 0.3. These limit values correspond to the same ranges of slope derived for D_{90}/d_b (Church and Jones, 1982). When Parker and Klingeman's (1982) value $\tau_*=0.035$ for D_{50} is used, the transport equation becomes:

$$S=0.058(D_{50}/d_b) \quad (7)$$

The range for the slope threshold then corresponds to 0.017 to 0.058.

Figure 9 shows that all the study data fall below theoretical transport lines using both $\tau_*=0.035$ and $\tau_*=0.05$ indicating that both

transport lines discriminate the field of transport from the field of no transport. The predicted ranges of maximum slope for bar formation using $\tau_* = 0.035$ and $\tau_* = 0.05$ are in close agreement. The slope threshold for bar formation observed for my study reaches (0.02) falls slightly below the range of maximum slope predicted by Church and Jones' model using $\tau_* = 0.05$, and falls within the range of maximum slope using $\tau_* = 0.035$ at the D_{50}/d_b limits given by Church and Jones (Figure 9).

Width to Depth Ratio Vs. Slope

Bars in wide reaches may be more stable than bars in narrow reaches because as flow converges around a bar in a narrow reach, locally higher shear stress may erode the bar and make it less stable. In a wide channel, flow around a bar does not significantly converge, since the channel is not as constricted. However, bars were found in reaches with W_b/d_b as low as eight (Figure 10) which is lower than values suggested by Jaeggi (15) and Parker (12). The difference between my study data and suggested values may occur because increased critical depth in narrow channels (low W_b/d_b values) could lead to bar formation. Church and Jones' (1982) theory implies that reaches with mean particle size greater than one third the critical depth cannot form bars. If critical depth is large relative to the mean particle size due to a narrow channel, bars would be more likely to form. This application of Church and Jones' model contradicts Jaeggi's and Parker's observation that bars tend to form in wide channels (due to less shear stress needed to entrain particles with less effects of bank friction). This contradiction may account, in part, for bars in the study reaches

forming in channels with lower width to depth ratios than the limits found by Jaeggi and Parker.

Gravel Bar Fields

Differences between Ikeda's (1975) relation of bar type to U_*/U_{*c} and $S(W_b/d_b)$ data are summarized in Figure 13. North coastal study reaches with no bars fall into the empirical field for braid bars because of the large grain sizes in these streams. The mean value of D_{50}/d_b for Swift Creek (reach 14), Stuart Fork (reach 15), Little Lost Man @ Gage (reach 12), and Hurdygurdy Creek (reach 5) is 0.07. This value is close to Church and Jones' (1982) value of 0.1 for the maximum D_{50}/d_b for bar formation and is over one and one half times as large as the average value of D_{50}/d_b in Ikeda's braid bars (0.04). It is also possible that the study reaches on these north coastal streams lack braid bars because they are too constricted by their valley walls to allow braiding. Large W_b/d_b promotes bar development because shallow depths associated with wide channels cause a decrease in the bed shear stress needed to entrain sediment. The W_b/d_b ratio for Ikeda's most narrow type I stream is 100. Average W_b/d_b for Ikeda's type I stream is 360, over 20 times as large as the average W_b/d_b (15.6) for Camp Creek, Stuart Fork, and Swift Creek.

Braid bars may form after excessive aggradation and channel widening due to large floods or debris torrents. Braid bars due to aggradation and channel widening have been observed in Black Butte gaging station (Lisle, 1981). As the bed degraded, a single channel

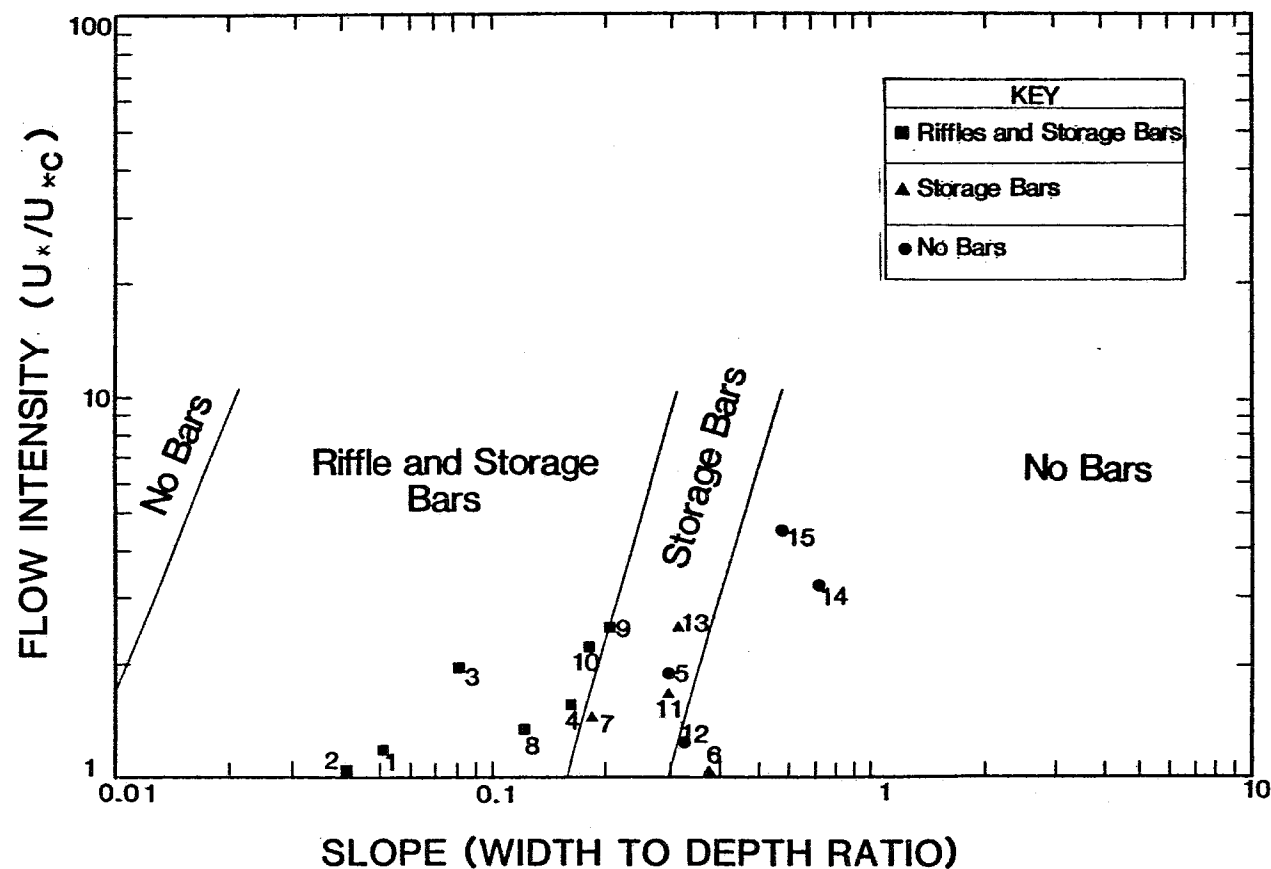


Figure 12. Flow Intensity (U_*/U_{*C}) vs. Channel Forming Factor ($S(W_b/d_b)$) Showing Bar Morphology for the Study Data, after Ikeda (1975). Bar types vary from riffles and storage bars at the lowest values of U_*/U_{*C} and $S(W_b/d_b)$, to storage bars only, to no bars at the highest values of U_*/U_{*C} and $S(W_b/d_b)$.

BAR TYPES IN IKEDA'S REACHES		BAR TYPES IN STUDY REACHES	REASONS FOR DIFFERENCES
I	Braid Bars	No Bars, Step-Pool Sequences	Low W_b/d_b supresses braid bars.
II	Alternate Bars with Riffle-Pool Sequences	Storage Bars, without Riffle-Pool Sequences	High D_s/d_b supresses bars.
III	Alternate Bars without Riffle-Pool Sequences	Storage Bars with Riffle-Pool Sequences	Low D_s/d_b (greater than sand) enhances bars.
IV	No Bars	No Data	
High W_b/d_b Low D_s/d_b		High D_s/d_b Low W_b/d_b	

Figure 13. Summary of Differences Between Ikeda's (High W_b/d_b , Low D_{50}/d_b) and Study Data's Results (Low W_b/d_b , High D_{50}/d_b).

was incised, and the braid bars were either laterally eroded or left as relict features. Thus, these bars were not stable features.

Study reaches containing storage bars without riffles may fall into the type II class (alternate bars with riffle-pool sequences) because the large D_s/d_b values present in the study reaches suppress riffle bars. Study reaches containing storage bars and riffles fall into Ikeda's type III class (alternate bars without riffle-pool sequences) because small gravel particle sizes (larger than sand) may enhance riffle bar formation. Reaches in Ikeda's type I and II classes have bed material composed mainly of sand. The difference in channel character between Ikeda's and my data probably accounts for the different channel morphology occurring at similar values of U_*/U_{*c} and $S(W_b/d_b)$.

CONCLUSIONS

Gravel bars in north coastal streams form under a distinctive set of limits and conditions. The major controls on riffle and storage bar formation in the straight, gravel bed study reaches are described below.

1. No bars form when slope is greater than 0.02 except for bars downstream of flow obstructions. All reaches containing riffles and pools also contain storage bars. However, riffles may be unstable in reaches with slopes near 0.02 which contain storage bars, since not all reaches with storage bars also contain riffles.
2. The maximum slope allowable for bar formation predicted using Church and Jones' (1982) model can be tested for D_{90}/d_b and D_{50}/d_b . The model using D_{50}/d_b is most theoretically accurate because Parker and Klingeman's (1982) value of $\tau_* = 0.035$ for D_{50} in a gravel pavement can be used rather than Shield's (1936) value $\tau_* = 0.05$, derived for D_{50} in a uniform bed of spherical grains. The slope threshold observed for bar formation in my study reaches (0.02) falls within the range of maximum slope (0.017-0.058) for bar formation predicted by Church and Jones' model using $\tau_* = 0.035$.

The slope threshold for bar formation observed for the study data (0.02) can be used to determine a limit value of D_{50}/d_b corresponding to the study data. Using $\tau_* = 0.035$ (the value derived for D_{50} in a gravel pavement) D_{50}/d_b is 0.35.

3. Transport lines, derived from Shields' equation for mobility, show flow conditions theoretically necessary for entrainment of particles. In the study reaches, all particle sizes are carried at bankfull flow.
4. Flow depth must be large enough to entrain particles and carry them to the crest of a bar. Bankfull flow is not able to build bars to a height corresponding to bankfull depth as suggested by Jaeggi (1982) ^{meanders?} and Simons and Richardson (1966). Storage bars reach a height of 71 ¹ percent bankfull depth, and riffles reach a height of 26 percent ^{straight reaches} bankfull depth.
- ✓ 5. Bars in the study reaches occur at width to depth ratios less than lower limits of $W_b/d_b=12$ or 15 (Parker, 1978; Jaeggi, 1982). Church and Jones' (1982) theory implies that channels with increased critical depth relative to particle size (as in channels with low W_b/d_b) can increase bar formation. This theory may account for bars in the study reaches forming at lower W_b/d_b values than predicted.
6. Bar morphology and occurrence depends on the relation between slope and bed material size. Riffles and storage bars form in reaches with gentle slopes and small particle sizes (larger than sand). No bars form in reaches with steep slopes and large particle sizes. A transitional field exists for storage bars only between the field of riffles and storage bars and the field of no bars.
7. Ikeda (1975) showed that bar type is dependent on flow intensity, U_*/U_{*c} , and a channel forming factor, $S(W_b/d_b)$. The north coastal study data fall into three of Ikeda's fields but they have different bar types. Reaches with no bars fall into Ikeda's braid bar class,

for two apparent reasons. It appears that bar development is inhibited by large D_s/d and low W_b/d_b . The mean grain size of the north coastal study reaches is over twice as large as the mean grain size in Ikeda's data, while the width to depth ratio is approximately 20 times less than the average W_b/d_b for Ikeda's braid bar reaches.

High rates of tectonic uplift and resulting rapid incision in north coastal California create narrow stream channels. Braid bars might form in these steep reaches with coarse bed material if the channel width was greater. These streams, constricted by valley walls, must have relatively gentle slopes and small particle sizes to form bars. In narrow channels with high gradients and large particle sizes, high magnitude events may cause excessive aggradation and channel widening, and braid bars may form.

8. Wolman and Miller (1960) suggest that, in certain streams, frequent events of moderate magnitude are more important than catastrophic events in determining channel morphology. In such a channel, frequent events probably transport the maximum particle size present, and repeated moderate events create riffle-pool sequences and storage bars. In contrast, bars are unlikely to form in stream channels with steep slopes, shallow depths, and large particle sizes where frequent moderate flow cannot pile clasts up on each other. Camp Creek, Hurdygurdy Creek, and Siskiyou @ Harry's Dredge and Paranoia Farm may have been affected by debris torrents during floods such as that which occurred in December 1964. Riffle-pool morphology was probably obliterated, and if bars occur at all, they are storage deposits along the edge of the channel. Therefore, it

appears that streams whose morphology is to some extent controlled by infrequent, high magnitude events (such as the 1964 flood) are less likely to have riffle bars with characteristic 5-7 channel width spacing. Further investigation on the relationship of debris torrents to bar formation is necessary to understand the processes involved before generalizations can be made.

9. Conditions favorable to riffle-pool and storage bar formation in gravel bed streams exist when the slope is gentle, width to depth ratio large, and particle size small relative to the flow depth. The relationship between these variables are major determinants of gravel bar occurrence. The relationships presented in this thesis are empirical, based on qualitative analysis of the study data. Future investigation is warranted to quantify the relationships presented.