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Effects of Aggradation and Degradation on Riffle-Pool Morphology in Natural Gravel Channels, Northwestern California

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After the flood of December 1964, 12 gaging sections in northern California widened as much as 100% and aggraded as much as 4 m, and then degraded to stable levels during a period of 5 years or more. As channels aggraded, bed material became finer, and low to moderate flow through gaging sections in pools became shallower, faster, and steeper. Comparisons of longitudinal profiles also show the diminishment of pools as well as a decrease in bar relief accompanying the excessive sediment load. As gaging sections degraded, hydraulic geometries recovered to a limited degree; full recovery probably depends on channel narrowing and further depletion of sediment supply. The hydraulic changes with aggradation indicate an increase in the effectiveness of moderate discharges (less than 1- to 2-year recurrence interval, annual flood series) to transport bed load and shape the bed. Bars become smaller, pools preferentially fill, and riffles armored with relatively small gravel tend to erode headward during falling stages and form a gentler gradient. Excess sediment can thus be more readily transported out of channels when additional contributions from watersheds are usuall slight.

A stream channel at grade provides the impetus to transport the supplied sediment load while maintaining a stable bed elevation [*Mackin,* 1948, p. 471]. Stream channels that scour and fill periodically are considered to be at grade unless over a period of years the channel bed progressively builds up (aggrades) or erodes (degrades) in response, usually to a change in sediment supply. States of ‘grade’ are easily recognized by the variation of bed elevation, but other channel adjustments to changes in sediment load may be equally important [*Leopold and Bull*, 1979]. For instance, *Grant* [1977] found that channel widening was a more consistent index of increased bed load activity in the Upper Waipawa River, New Zealand, than bed elevation. A change in bed elevation is, however, a useful indicator that channel characteristics are responding to a change in sediment load.

Channel roughness is a key factor affecting the efficiency to transport sediment. It thereby influences the overall capacity of a river to transport sediment. The shapes and spacing of some bed forms seem to create the maximum resistance to flow [*Davies,* 1980]. The size of bed forms, however, is related to sediment properties and flow conditions. The adjustment of macro-bed forms (bars) in gravel channels to sediment load is not well understood. In sand-bedded channels, ripples and dunes deform in response to changes in flow and sediment transport during nearly all stages. In gravel bed channels, bed load transport and bed form development generally occur only during relatively high stages because of channel armoring [*Parker and Peterson,* 1980].

Bars, which are large, relatively stationary bed forms, are the primary roughness elements in gravel channels. Migrating dunes are thought to be poorly developed or absent [*Parker et al.,* 1982]. The influence of bars as roughness elements is greatest at low flow [*Parker and Peterson,* 1980] when ponding of water in pools behind bar crests produces flows that are deeper and slower than would otherwise exist [*Bathurst,* 1981]. Because of their size and mobility, bars deform slowly and are usually adjusted to long-term trends in sediment load and flow conditions. Therefore they are relatively stable. Furthermore, in most geomorphic environments, transport capacity usually exceeds sediment supply in gravel streams [*Shen*, 1971]. Consequently, little adjustment in bar roughness is required to accommodate normal variations in sediment load. However, such stability does not exist during progressive aggradation when transport capacity is exceeded. Resulting changes in bar roughness may be anticipated but have not been adequately described.

The flood of December 1964 to January 1965 was the most damaging flood of the century in northwestern California, producing record or near-record runoff (commonly greater than 4 m^3/s km^2) and causing extensive landsliding in the mountainous, highly erosive basins [*Waananen et al.,* 1971]. In comparison with the latest historic flood of equal or greater magnitude (1861), the 1964 flood caused a disproportionate amount of hillslope and streambed erosion [*Harden et al.,* 1978]. Gaging sections in this region aggraded as much as 4 m and then degraded to stable levels equal to or higher than preflood levels within time spans ranging from 5 years to periods expected to be 2 decades or more [*Hickey,* 1969; *Nolan and Janda,* 1979; *Kelsey,* 1980; *Lisle,* 1981].

During the past three decades populations of all species of anadromous salmonids in northern California have declined by one half or greater largely because of the deterioration of habitat. A highly pronounced riffle-pool sequence provides the cover and diversity of substrate and hydraulic conditions that meet the various requirements of life stages of salmon and trout. Heavy sedimentation is suspected of diminishing riffle-pool sequences, thereby causing a severe deterioration in the resources of gravel streams. Documentation of changes in riffle-pool sequences, however, is scanty. Fishermen in this area lament the filling of pools in many streams. *Kelsey* [1980] observed from aerial photographs that pools in the Van Duzen River became more closely spaced as a result of aggradation associated with the 1964 flood.

Riffle-pool sequences are often created by bars extending over the full channel width. The position and orientation of

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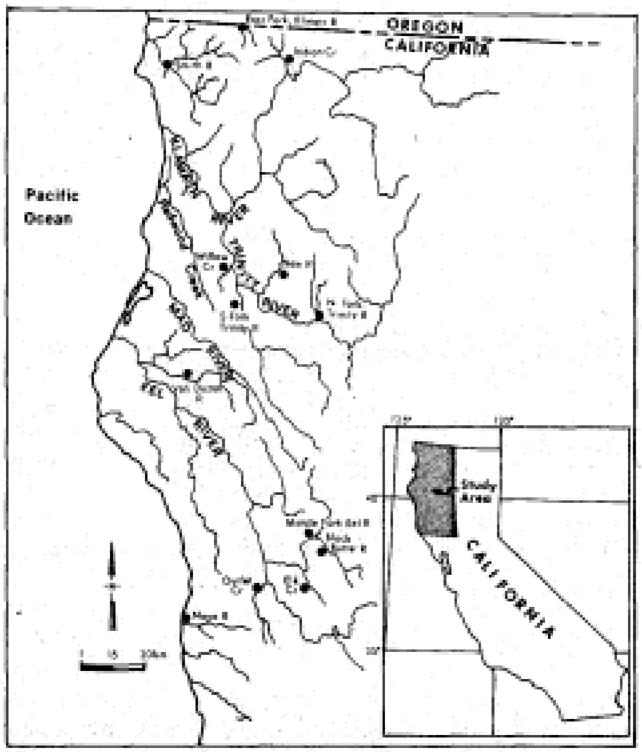

Fig. 1. Locations of gaging stations in this study.

the crest of such bars depend on reworking of the bar surface during receding flows. At low to moderate flows, the submerged bar crest forms the control section for the pool upstream and often forms the downstream riffle crest. Thus the pool is on the 'stoss' side of the submerged portion of the bar; the rife is on the 'lee' side. High-amplitude bars generally form voluminous pools and steep riffles.

By using data gathered at gaging sections, this paper investigates changes in pools and riles resulting from aggradation and degradation of natural gravel channels in northwestern California after the 1964 flood. Evidence for the diminishment of riffle-pool morphology is first presented. Later sections indicate that mean hydraulic variables at gaging sections in pools also show diminishment of pool characteristics. Changes in pools and riffes are then related to bar profiles and to changes in bed load transport. Thirteen gaging stations that aggraded 1 m or more and have long enough records to show an episode of aggradation and degradation were used to provide data for cross sections and mean hydraulic variables (Figure 1, Table 1). Longitudinal thalweg profiles were surveyed at some stations to relate changes at the gaging section to rife-pool morphology.

CHANGES IN CHANNEL MORPHOLOGY

Channels invariably widened as they aggraded, some as much as 100% [*Nolan and Janda,* 1979; *Kelsey,* 1980; *Lisle,* 1981]. Alluvial channels widened greatly but narrowed in some cases as they degraded. Channels with nonalluvial banks widened less, as little as 7%, but were not observed to narrow with degradation because, in general, hillslope processes are slow in replacing eroded streambank material and because newly formed banks and riparian vegetation are vulnerable to erosion at high flows confined within the steep valley walls [*Lisle,* 1981]. Narrow valley bottoms inhibit widening of sufficient breadth to accommodate extensive meandering or braiding. In the examples used in this investigation, then, adjustments to the sediment load by widening and by changes in channel pattern were constrained. Changes in channel morphology and in mean hydraulic variables reported herein occurred in single straight channels that widened no more than 100%.

TABLE 1. Drainage Area; Period of Records, and Location of 12 Gaging Stations, Northwestern California

Gaging Stations	Drainage Area, km^2	Period of Daily Records	Change in Gaging Section Location
114685 Noyo River near Fort Bragg, Calif.	276	8/51 to present	none
114722 Outlet Creek near Longvale, Calif.	417	10/56 to present	none
114728 Elk Creek near Hearst, Calif.	219	8/64-9/73	none
114729 Black Butte River near Covelo, Calif.	420	10/58-9/75	none
114739 Middle Fork Eel River below Black Butte River near Cavelo, Calif.	951	8/51-9/67	none
114785 Van Duzen River near Bridgeville, Calif.	575	10/50 to present	moved 3.9 km down stream, 10/1/65
115215 Indian Creek near Happy Camp, Calif.	311	12/56 to present	moved 1.3 km down stream, 9/20/69
115265 North Fork Trinity River at Helena, Calif.	391	1/57 to present	none
115274 New River at Denny, Calif.	448	6/59-9/69	none
115290 South Fork Trinity River near Salyer, Calif.	2326	10/56-9/67	none
115298 Willow Creek near Willow Creek, Calif.	106	8/59-9/74	moved 2.3 km upstream after 12/22/64
115325 Smith River near Crescent City, Calif.	1577	10/31 to present	10/72-9/79 at site 0.6 km upstream
143725 East Fork Illinois River near Takilma, Ore.	110	10/26 to present	moved 1.0 km upstream, 8/23/65

Gaging sections generally changed from poollike forms (having a pronounced thalweg) before aggradation toward more rifflelike forms (wider than before, with flat cross-sectional profiles). This change was most evident during peak aggradation (Figure 2). A thalweg was usually reexcavated during the period of degradation. *Kelsey* [1980] observed the incision of a thalweg over long reaches of the Van Duzen River during its period of degradation. There and elsewhere, small-scale bars were formed within large bars that were formed during the 1964 flood. Alluvial sections in which width most substantially increased show the least tendency to return to their preflood bottom profiles.

Thalweg profiles (Figure 3*a*) were surveyed around four gaging sections in order to compare two presently aggraded channels (Elk Creek and Van Duzen River), or ones with excessive in-channel sediment, with two channels (Outlet Creek and North Fork Trinity River) that had aggraded and then degraded to stable levels. The presently aggraded channels were degrading at the time of survey [*Kelsey*, 1977; *Lisle*, 1981]. Pools are deeper and longer in the degraded channels than in the aggraded channels (Figure 3*a*). Residual thalweg depth (the thalweg depth of pools when discharge is zero [*Bathurst*, 1981] is proportionately greater in the degraded channels than in the aggraded channels at approximately equivalent low flows (Table 2). Reaches within each profile were classified as (1) pools (deep reaches with nearly horizontal water surface), (2) riffles (steep, shallow reaches of coarse bed material), or (3) runs (moderately deep reaches whose bed and water surface gradients are roughly equal to the average of the entire profile) (Table 2). The two degraded reaches show a higher percentage length of channel as pools and a much lower percentage length as runs than the presently aggraded reaches.

In many of the reaches, and particularly in those containing the gaging station, a deep pool of one or more channel widths in length lies upstream of a reach shelving up to the control section (Figure 3*b*). The reaches downstream of the pool deeps, where gaging sections are usually located, apparently act as in-channel depositional sites for relatively fine bed load. In the aggraded channels these reaches are characterized as runs, but in the degraded channels they are characterized as the shallower sections of pools.

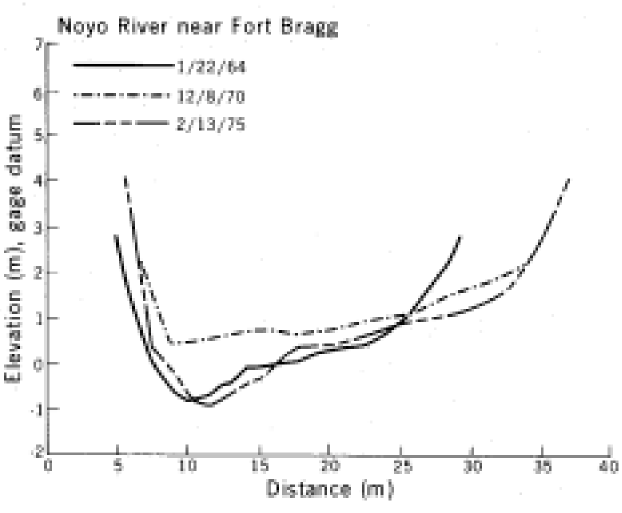

Fig. 2. Noyo River gaging section before aggradation, at maximum aggradation, and after degradation to a stable level. The poollike characteristics before aggradation recovered somewhat when the thalweg incised to the original level, but the active channel remained at its maximum width.

A comparison of profiles suggests that aggradation resulted in a diminishment of the morphological contrasts of riffles and pools. Gaging sections in pools became more rifflelike and thus more closely represented the 'average' section of the local reach of river. These changes indicate a decrease in bar relief.

CHANGES IN MEAN HYDRAULIC VARIABLES

The variations of mean hydraulic variables with discharge at a station often fit linear power functions, e.g., $w \propto Q^b$, $d \propto Q^f$, $u \propto Q$, in which w = width, d = mean depth, u = mean velocity, and Q = discharge, that are collectively known as the hydraulic geometry [*Leopold and Maddock*, 1953]. The hydraulic exponents b, f, and m are useful for comparing the rate of change of mean hydraulic variables with discharge in channels of different size.

Knott [1971, 1974] compared hydraulic geometries of aggraded gaging stations in the Trinity and Middle Fork Eel basins between periods before and after the 1964 flood. After the flood, mean velocity and width were greater and mean depth was less for a given low to moderately high discharge. On this basis, he concluded that bed load transport capacity had increased. The following treatment of additional hydrau-lic data focuses on two problems: how hydraulic changes at a cross section accompanying aggradation and degradation relate to widespread changes in channel form, and whether an increase in transport capacity exists at discharges high enough to transport geomorphically significant volumes of sediment and thus counter further aggradation.

Data from 12 gaging stations (Table 3) show changes in hydraulic geometry accompanying aggradation and degradation after the 1964 flood. Sets of values of hydraulic variables for each station were separated into three groups corresponding to phases of the aggradation episodes: (1) the 'preaggradation period' predating December 1964, (2) the 'peak aggradation period' corresponding to maximum bed elevations, and (3) the 'postaggradation period' correspond-ing to degraded or lower, stabilized bed elevations.

Eight of the eleven stations which provide data for the preaggradation and peak aggradation periods show an increase in mean velocity and width and a decrease in mean depth at low to moderate discharges during the peak aggradation period (Figure 4). No significant changes are apparent at Outlet Creek. The lack of a significant change in the hydraulic geometry of the Van Duzen station will be explained later. Bank erosion caused a far greater change in active channel width than in the rate of change of water surface width with discharge, which is controlled in part by the cross-sectional profile of streambanks. In seven of eleven sections, values of b (hydraulic exponent for width) did not change significantly with aggradation (Table 3). Channel widening can decrease depth up to the point where the increase in relative roughness (ratio of bed material diameter to depth) causes a decrease in velocity [*Madej*, 1978]. At the Willow Creek section where width doubled, depth decreased as much as 50% at low flow, but, unlike other stations, velocity at a given discharge remained approximately constant.

Compared to the preaggradation period, velocity increased at a lower rate with increasing discharge (m decreased) at eight out of eleven stations, and depth increased

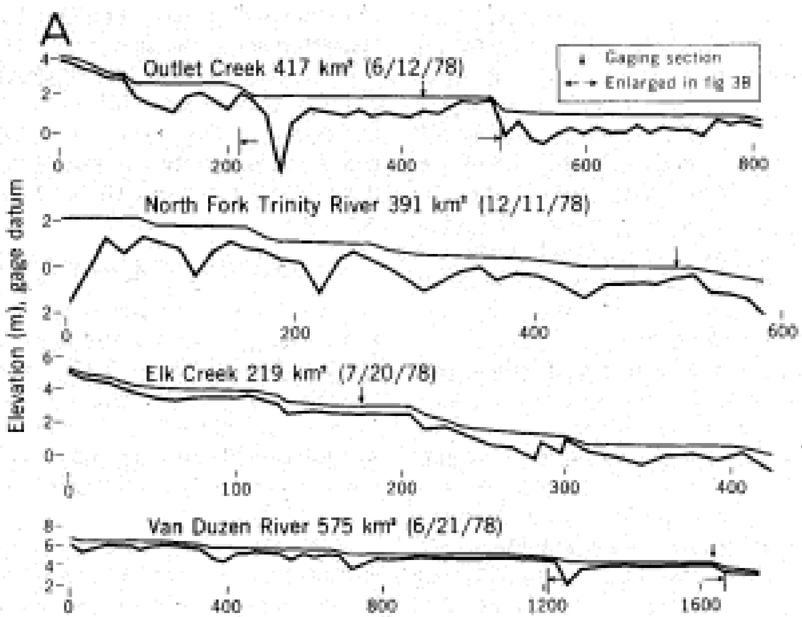

Fig. 3*a*. Thalweg profiles of two channels degraded to stable levels (Outlet Creek and North Fork Trinity River) and two aggraded channels (Elk Creek and Van Duzen River), drawn at the same vertical exaggeration. The profiles, surveyed at low flow, include four rife crests or a distance of at least 20 channel widths.

at a higher rate (*f* increased) at seven stations during the peak aggradation period (Figure 4; Table 3). There was no significant change in the hydraulic exponents *m* or *f* in the other stations which, except for Middle Fork Eel River, aggraded no more than 1 m. Of those that show change in *m* or *f* , values of the ratio of *m* for the preaggradation period to *m* for the peak aggradation period range from 1.2 to 2.9, averaging 1.8. Values of the corresponding ratio for *f* range from 0.5 to 1.1, averaging 0.7. At the Smith River station where the *f* ratio is greater than 1 and *f* did not change significantly, the values for *f* are suspect because the relation of depth to discharge fits a quadratic equation better than a linear one: Still, values of depth at low discharges are less here for the aggradation period and, at higher discharges, converge on the values of depth for the preaggrada= tion period.

Six stations provided data for the postaggradation period, but one (East Fork of the Illinois River) provided no data for the preaggradation period with which to compare. All but Outlet Creek show a decrease in velocity and an increase in depth at a given low to moderate discharge accompanying degradation (Figure 4, for example), indicating a return toward the hydraulic geometry of the preaggradation period. Consistent with this recovery, *m* increased at three stations and *f* decreased at two (Table 3). The other cases show no significant changes.

Values of mean velocity and mean depth for the postaggra dation period plot between those for the preaggradation and peak aggradation periods at sections of North Fork Trinity (Figure 4), Noyo, and Smith Rivers. In these three sections, width remained 14-22% greater after degradation than before aggradation [*Lisle*, 1981]. A residual increase in width after degradation would logically lead to a corresponding decrease in depth. However, one would expect mean velocity to also decrease because of the increase in relative roughness. Instead, mean velocity at low to moderate flows remained higher after degradation than before aggradation in these three cases.

The changes in depth and velocity reflect corresponding changes in hydraulic friction and channel roughness. Friction here is measured by the Darcy-Weisbach friction factor:

$$ff = \frac{8gdS}{u^2}$$

in which d = mean depth which approximates hydraulic radius, S = energy gradient approximated by the reach-averaged water surface slope, and u = mean velocity Friction decreased at eight of ten gaging sections at low to moderate flows as a result of aggradation. The other sections

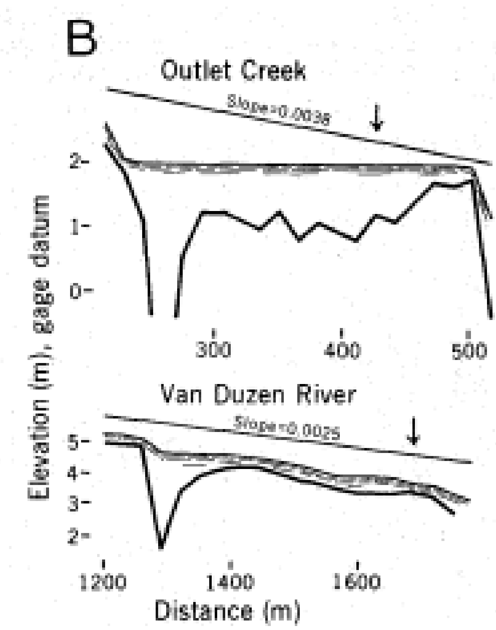

Fig. 3*b*. Profiles of reaches containing gaging sections (from Figure 3*a*). The reach just upstream of the Outlet Creek gaging section is the shallow section of a pool; the corresponding reach of the Van Duzen River gaging section is a run with water surface and bed slope parallel to the slope of the entire reach shown in Figure 3*a*.

TABLE 2. Reach Gradient, Length of Reach Classified as Pools, Riffles, and Runs, and Depth Ratio for Gaging Stations

Gaging Station	Reach Gradient	Length of Reach			Residual Thalweg Depth/Total Thalweg Depth
		Pools	Riffles	Runs	
Outlet Creek*	0.0038	79%	15%	6%	0.67
North Fork Trinity River*	0.0033	64%	13%	23	0.50%
Elk Creek†	0.0059	40	8%	52	0.26
Van Duzen Rivers†	0.0025	45%	19%	57%	0.36

See Figure 3*a*.
*Degraded.
†Presently aggraded.

show no significant change. In five of seven sections with available records, friction increased to a lesser degree after degradation (Figure 4, for example); the other two sections did not change significantly.

Changes in the relation between friction and discharge ($ff \propto Q^y$, where *y* is the hydraulic exponent) could not be determined precisely because of the lack of measurements of energy gradient over a range of discharges. The friction exponent *y* is equal to $f + z - 2m$, where *z* is the hydraulic exponent for energy gradient.. Because *z* could not be evaluated, it is given a value of zero (energy gradient assumed constant), and thus *y* equals $f - 2m$. Qualitative changes in *z* are inferred from the low-water longitudinal profiles (Figure 3*b*). At low flow, the local water surface slope over reaches upstream of riffle crests, where gaging sections are located, is steeper relative to the length-averaged slope in aggraded channels than in channels that have degraded to stable levels. Values of *z*, therefore, would be less in corresponding reaches of the aggraded channels because of their smaller range of values of energy gradient between low and high discharge. If *z* decreases with aggradation, as logically follows, then the increase in $f + z - 2m$ would be less than if *z* were assumed equal to zero. This difference, however, is not expected to be great enough to qualitatively change the trend in the relationship of friction with discharge during aggradation.

Before aggradation, friction at gaging sections decreased with discharge; after degradation, it varied to a lesser degree (Figure 4). In most sections, lack of significant relations between friction and discharge invalidates a statistical comparison of values for *y* between periods. Among the sections with significant relations, values for *y* increased significantly with aggradation in three of five sections, and decreased in only one of three sections with degradation (Table 3). The other sections did not change significantly.

A decrease in bed material size accompanied aggradation in many channels [*Ritter*, 1968; *Nolan and Janda*, 1979; *Kelsey*, 1980, p. 1181]. A decrease in flow resistance resulting from the reported decrease in grain roughness is consistent with the increase in mean velocity and decrease in mean depth and friction factor observed at most of the gaging stations. It does not, however, account for the changes in the hydraulic exponents for velocity, depth, and friction. Therefore, hydraulic changes observed at gaging sections were probably not the direct result of a decrease in grain roughness. Instead, they reflect a decrease in bar roughness which creates the greatest friction at relatively low stages [*Parker and Peterson*, 1980]

Riffles and pools represent the extremes of a spectrum in the stage-dependent regimes of hydraulics and sediment transport. At low or moderate discharges in a given reach, width, mean velocity, and slope over riffles are characteristically greater, and depth is less than in pools. As discharge increases; mean velocity generally increases at a lower rate over riffles than in pools, and, by the same comparison, mean depth increases at a higher rate. Energy gradient generally decreases with discharge at rifes and increases at pools, so the corresponding values tend to become equal at high flow. Accordingly, values off for riffles are characteristically higher and values of *z* and m are lower than those for *pools* [*Knighton*, 1975; *Richards*, 1976]. Differences in mean hydraulic variables generally decrease with discharge as a riffle-pool sequence is submerged or 'drowned out.'

Despite a variety of changes in cross-sectional form [*Lisle*, 1981], most gaging sections show a change in hydraulic geometry from poollike characteristics (high *m*, low *f*) to more rifflelike characteristics accompanying aggradation. The same trend with respect to *z* can be inferred from the low-water longitudinal profiles (Figure 3*b*) as previously described. Moreover, the hydraulic geometries for mean velocity converge at a recurrence interval (Table 3) that, except for the New River, approximately corresponds to the disappearance of the stepped water surface topography created by rife-pool sequences [*Leopold et al.*, 1964, p. 206; *Bray*, 1979]. Differences in the morphology and mean hydraulics of the gaging sections between aggraded and nonaggraded states closely resemble differences in the same characters between pools and riffles. This resemblance indicates that aggraded pool sections became more rifflelike. The hydraulic geometry of the Van Duzen gaging section shows no change probably because it is located near a riffle crest (Figure 3*b*).

CHANGES IN BED LOAD TRANSPORT RATES

At a given stage above the entrainment threshold, the efficiency with which stream power (γQS, where γ = the specific weight of water) is used to transport bed load increases as the ratio of depth to bed load particle size decreases [*Bagnold*, 1977]. An increase in velocity or the width/depth ratio results in a greater transport capacity at a given stream power. On the basis of the Meyer-Peter and Muller equation, *Knott* [1974] concluded that the changes in hydraulic geometry at stations in the Trinity River basin constituted an increase in bed load transport. The increase apparently existed for flows up to the value of discharge, Q_i, corresponding to the convergence of hydraulic geometries for preaggradation and peak aggradation periods (Figure 4).

Values of discharge corresponding to the initiation of gravel transport at three stations (Black Butte River, Middle Fork Eel River, and North Fork Trinity River [*Knott*, 1971,

TABLE 3. Hydraulic Exponents and Discharge and Recurrence Interval Corresponding to the Convergence of Hydraulic Geometries for Preaggradation and Aggradation Periods at 12 Gaging Stations, Northwestern California

Gaging Station	Hydraulic Exponents[a]												Convergence of Hydraulic Geometries	
	Preaggradation				Aggradation									
	m	f	b	y	m	f	b	y	m	f	b	y	Q_c, m^3/s	Recurrence Interval, years
114685 Noyo River	0.45[b]	0.36	0.19[g]	−0.54[b]	0.25[c]	0.64[c]	0.11[c]	0.14[d]	0.30	0.56	0.15	−0.03[e]	260	2.0
114711 Outlet Creek[f]	0.50[g]	0.42[e,g]	0.08[c,g]	−0.59[c,g]	0.47[c]	0.45[c]	0.08[c]	−0.49[c]	0.38	0.21[e]	0.05	−0.57[b]	. . .	. . .
114729 Black Butte River[f]	0.37	0.49	0.13[g]	−0.26	0.26	0.67	0.08	−0.15[e,g]	. . .	. . .	. . .	. . .	510	3.8
114720 Middle Fork Eel River[f]	0.41	0.42[g]	0.15[g]	−0.39[b]	0.22	0.43	0.35	−0.02[e,g]	. . .	. . .	. . .	. . .	470	1.2
114785 Van Duzen River	0.32[g]	0.52[g]	0.14	−0.12[e,g]	0.34	0.52	0.10	−0.17[e]	. . .	. . .	. . .	. . .	. . .	. . .
115215 Indian Creek	0.49	0.45	0.12[g]	−0.54[b,g]	0.31[b]	0.52	0.17[c]	−0.10[e,h]	0.64	0.06	0.30	−1.21	150	1.4
115265 North Fork Trinity River[f]	0.55[g]	0.39[c]	0.06[c,g]	−0.71[b,c]	0.19[b]	0.75	0.06[c]	0.38[e,h]	0.42	0.52	0.06	−0.33[e,h]	160	1.5
115274 New River[f]	0.47	0.35	0.17[g]	−0.58[c,i]	0.34	0.41	0.24	−0.27	. . .	. . .	. . .	. . .	1400	20
115290 South Fork Trinity River[f]	0.46	0.39	0.17[g]	−0.53	0.13	0.71	0.12	0.36	. . .	. . .	. . .	. . .	1400	4.3
115298 Willow Creek	0.40[g]	0.21	0.41	−0.60	0.38	0.56	0.07	−0.19[e]	. . .	. . .	. . .	. . .	. . .	. . .
115325 Smith River	0.59[b,c]	0.30[b,c,g]	0.11	−0.89[b,c]	0.32	0.28[b,c]	0.40	−0.36	0.58[b]	0.25[b]	0.17	−0.90	450	1.0
1143725 East Fork Illinois River	. . .	. . .		. . .	0.40[c]	0.46[c]	0.14[c]	−0.34[c,i]	0.47	0.44	0.08	−0.51	. . .	. . .

[a] m, f, and y are hydraulic exponents for velocity, depth, and friction, respectively.
[b] More closely fits quadratic equation based on partial F test at 0.05 level.
[c] Does not differ significantly with regression value for postaggradation period at 0.02 level.
[d] Values of friction lower than those for postaggradation period.
[e] Not statistically significant at 0.05 level.
[f] Values for earlier period from *Knott* [1971, 1974].
[g] Does not differ significantly with regression value for aggradation period at 0.02 level.
[h] Values of friction lower than those for preaggradation period.
[i] Exponent values not significantly different; intercept values significantly different at 0.02 level.

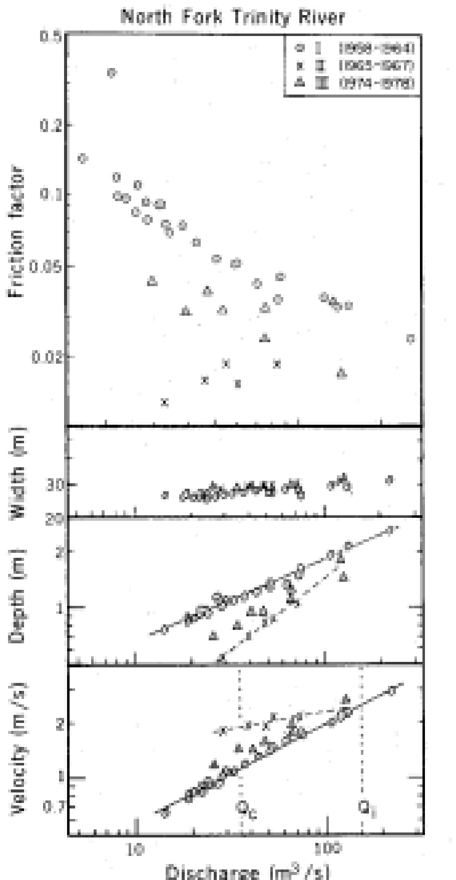

Fig. 4. Relations of width, mean depth, and mean velocity with discharge for preaggradation (I), peak aggradation (II), and postaggradation (III) periods. *Q*, is the value of discharge corresponding to the initiation of gravel transport; *Q*; is the value corresponding to the intersection of hydraulic geometries for the preaggradation and peak aggradation periods.

1974]) are 2-24% of the values of *Q*;. The recurrence intervál of Q_i (1.0-20 years) for the other five stations (Table 3) seems longer than that for minimum discharges capable of entraining gravel, considering that streams of north coastal California with basin areas smaller than these usually transport important volumes of gravel several times each year [*U.S. Geological Survey,* 1975*a, b,* 1976, 1977; T. E. Lisle, unpublished data, 1981]. Therefore, bed load transport capacity apparently increased for flows that transported volumes of bed load important enough to affect channel morphology.

Despite the lack of direct, evidence, bed load transport at discharges up to moderately high values seems to have increased as a result of aggradation. The accompanying reduction of bed material size decreased the threshold of entrainment when excess sediment in the channel could be transported efficiently. Channel armoring may have somewhat retarded the increase in bed load transport, but transport capacity for discharges above the threshold of entrainment increased, at least at the three stations with bed load data. The changes in hydraulic geometry caused by aggradation signifies an important increase in transport capacity between discharges corresponding to the initiation of bed load transport and the convergence of hydraulic geometries. As bed load transport capacity increased proportionally much more for low discharges than for high discharges, it must have increased with discharge at a lower rate than before aggradation.

Although, over the long term, each section in a reach of channel passes an equal amount of bed load, the relationship between sediment transport and discharge may differ between sections. Pools in the East Fork River, Wyoming, fill at low flow and scour at high flow; riffles fill at high flow and scour at low flow [*Andrews,* 1979; *Lisle,* 1979]. Andrews inferred that the sediment-discharge relationships for scouring sections have steeper slopes than those for filling sections. Differences in the slopes of the sediment discharge relationships were correlated with the rate of change of mean velocity. *Keller* [1971] used values of bottom velocity and *Lisle* [1979] used values of mean shear stress to support a hypothesis that the transport competence over a riffle, which is relatively high at low flow, is equalled by that in a pool at high flow. Riffles thus tend to have lower slopes of sediment transport-discharge relationships than pools. Therefore, aggradation caused gaging sections in pools to become more rifflelike with respect to the decrease in the slope of sediment transport-discharge relations.

DISCUSSION

Aggradation increased the effectiveness of relatively low flows to form the channel and to transport sediment. It did so because the decrease in the grain size of the surface of bed load deposits in the active channel reduces the threshold of bed load transport.

Evidence that pool sections became more rifflelike in hydraulic characteristics as they aggraded supports the earlier supposition, based on channel morphology and changes in friction, that aggradation causes a decrease in bar relief. One explanation for changes in bar amplitude offered here stems from observations by *Parker and Peterson* [1980] that gravel bars are generally formed only at flood stages. At lower stages, bed load transport rates are too small to cause important modifications. As bed load transport rates at relatively low stages increase with aggradation, bar formation at low stages should have become increasingly effective. It is reasonable to expect that bars formed at low stages are relatively small in amplitude. After the gaging sections degraded, hydraulic variables again did not quite fit preaggradation relations, probably because high supplies of bed load persisted and, in most cases, channels did not narrow during or after degradation.

Explanation of why aggradation decreases pool volume is provided by literature on scour around bridge piers. Pools in gravel streams in forested mountainous terrain are often formed around large obstacles in the channel, such as outcrops, boulders, and large organic debris, that cause enough scour to substantially alter bar structure [*Keller and Swanson,* 1979; *Keller and Tally*, 1979]. In the case of scour holes around newly placed bridge piers, scour depth progress-sively increases with stage up to the ambient critical threshold of bed load transport, thereafter decreases, but increases again with increasing velocity [*Jain and Fischer*, 1980]. A balance between hydraulic scour, and infilling by transported sediment thus determines equilibrium scour depth. Increased bedload transport at relatively low flows may be expected to reduce the depth of pools maintained by turbulent stress generated by obstacles as well as channel bends or bars.

Possible change in riffle profiles can be inferred from decreases in bed material size during aggradation and current understanding of gravel bar formation. Bar fronts forming riffles at low to moderate flows are built up and steep ened during flood flows of bankfull stage and higher [*Parker and Peterson*, 1980]. The fronts are then reworked into gentler riffles at lower flows. In the vicinity of the aggraded gaging sections, there were low-flow channels that apparently eroded headward into bar fronts a distance as- long as nearly, one channel width. This evidently occurred during receding stages. Simultaneous measurements of bed load transport rates taken during receding flows above and below a riffle in Jacoby Creek, northern California, have shown relatively large rates below the riffle (T. E. Lisle, unpublished data, 1981). *A* reduction in size of bed material would cause a decrease in riffle gradients and a lengthening of riffles headward. There was little difference in proportional riffle lengths of the longitudinal profiles (Table 1), but some riffles may have attenuated and become runs in adjacent reaches. The outcome of headward erosion of bar fronts is the further diminishment of pools-the control section or sill which ponds water in pools is lowered and most material eroded from riffles during receding flows is likely to be deposited in downstream pools.

The change in hydraulic conditions recorded in gaging sections in the downstream portion of pools probably manifests a widespread adjustment in channel morphology to increased sediment load. The increase in bed load transport capacity provides an effective mechanism for transporting excess sediment out of channels during the moderate flows of each year when additional contributions from watersheds are usually slight. All of the available gaging station records for this area show degradation during years without large floods [*Lisle*, 1981]. The Smith River station, for example, shows three episodes of aggradation, each begun by one or more large floods and followed by a period of degradation devoid of large floods.

CONCLUSIONS

Although bed load transport rates large enough to form gravel bars usually occur at flood discharge, bars offer the greatest friction and produce the greatest degree of hydraulic nonuniformity at low flow. An overwhelming sediment load in rivers of northern California decreased bar roughness and thereby diminished the morphologic and hydraulic contrasts in riffle-pool sequences. A decrease in bed material size and an abundant in-channel supply of sediment preferentially increased bed load transport at relatively low discharges and thus increased their effectiveness to form the channel at receding stages. Under these conditions, bar relief decreased as pools filled and riffles eroded headward. Channel friction was therefore reduced preferentially at low discharges when proportional increases in bed load transport were greatest. These adjustments in bar topography, culminating in an increased efficiency of sediment transport, thus hasten the net erosion of aggraded channels during the moderate flows of each year.

Transport capacity decreased and bar relief apparently increased when degradation signaled a waning supply of sediment in the channels. However, in many basins full recovery to preflood morphology must await the natural reconstruction of eroded stream banks and a reduction of erosion and sediment supply.

States of grade have been recognized by changes in bed elevation, but channel adjustments to large variations in sediment load involve nearly all hydraulic and morphologic variables at the scale of a reach.. In the case of these gravel bed streams with limited variations in width and channel pattern, the most fundamental changes to increased sediment load have been an increase in transport efficiency coupled with a decrease in channel roughness.

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