GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO.2, PAGES 227-230, JANUARY 15, 1999

Streamflow trends in the United States

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Abstract. Secular trends in streamflow are evaluated for 395 climate-sensitive streamgaging stations in the conterminous United States using the non-parametric Mann-Kendall test. Trends are calculated for selected quantiles of discharge, from the 0^{th} to the 100^{th} percentile, to evaluate differences between low-, medium-, and high-flow regimes during the twentieth century. Two general patterns emerge; trends are most prevalent in the annual minimum (Q_0) to median (Q_{50}) flow categories and least prevalent in the annual maximum (Q_{100}) category; and, at all but the highest quantiles, streamflow has increased across broad sections of the United States. Decreases appear only in parts of the Pacific Northwest and the Southeast. Systematic patterns are less apparent in the Q_{100} flow. Hydrologically, these results indicate that the conterminous U.S. is getting wetter, but less extreme.

Introduction

Floods and droughts cause more damage annually in the United States than any other natural disaster. There is an increasing trend in both flood damage and drought vulnerability (Federal Interagency Floodplain Management Task Force, 1992; U.S. Army Corps of Engineers, 1995; Wilhite, 1997). Most of the flood damage increase stems from continuing urban and suburban development on floodplains and the drought vulnerability increase is from development in regions of lower renewable water supplies. However, there is also a perception that extreme hydrologic events are increasing in frequency and/or magnitude.

Most documentation of trends in surface water hydrologic conditions has focused on monthly and annual mean discharge or the timing of monthly mean discharge (Chiew and McMahon, 1996; Lettenmaier *et al.*, 1994; Lins and Michaels, 1994). Since the 1940's, the general pattern has been toward an increase in mean discharge in the autumn and winter months in most regions of the conterminous United States. Systematic analysis of trends across the spectrum of streamflows, including flood- and low-flows, has received little treatment. Significantly, however, the Mississippi floods of 1993 and the widespread flooding during 1997 in the West, Upper Midwest, and the Ohio Valley, as well as the widespread 1988 and 1995-96 drought, gave rise to speculation that floods and droughts are increasing; possibly in response to greenhouse warming. We consider the question of any changes in hydrologic regime by determining whether trends have occurred in streamflow over a range of discharge quantiles.

Data and Methods

A compilation of daily discharge records, relatively free of such anthropogenic influences as watercourse regulation, diversion, ground-water pumpage, or land use change, was developed by the U. S. Geological Survey (USGS) to study climatically-induced variations in U. S. surface-water conditions (Slack and Landwehr, 1992). Known as the Hydro-Climatic Data Network (HCDN), it includes data from more than 1500 streamgages. We use a subset of the HCDN consisting of daily mean discharge from 395 stations that provide broad spatial coverage of the hydrology of the United States. The 395 stations represented the maximum number furnishing continuous daily records over the 50-year period 1944-1993, with a decreasing number of stations providing data at longer time periods; 193 at 60 years (1934-93), 70 at 70 years (1924-93), and 34 at 80 years (1914-93). Although more than 395 stations had continuous data for periods less than 50 years, we wanted to maximize sample size and maintain site continuity over 30-, 40-, and 50-year periods, while not compromising spatial coverage.

Trends in the HCDN records are evaluated using the non-parametric Mann-Kendall test. The test examines whether a random response variable monotonically increases or decreases with time. It is a rank-based procedure, resistant to the influence of extremes, and good for use with skewed variables. No assumption of normality is required, although there must be no serial correlation for the resulting p-values to be correct (Helsel and Hirsch, 1992). These characteristics make it particularly appropriate for use with streamflow data sampled up to one year apart.

Our approach to the assessment of trends in streamflow involves two distinct elements. First, we test for trends in 7 quantiles of the streamflow distribution, by selected decimals, from the annual minimum (daily mean) (Q_0) to the annual maximum (daily mean) (Q_{100}). This includes the 90^{th} (Q_{90}), 70^{th} (Q_{70}), 50^{th} (Q_{50}), 30^{th} (Q_{30}), and 10^{th} (Q_{10}) percentiles. In so doing, we derive a more complete picture of how the streamflow regime is changing over the entire discharge spectrum. Second, we evaluate interdecadal streamflow variability by calculating the quantile trends for 30-, 40-, 50-, 60-, 70-, and 80-year periods, all ending in 1993. This provides some insights as to how the characteristics of hydrologic trends during the century are affected by the period-of-record.

Results

Trend test results, by quantile and period-of-record, are summarized in Table 1. Moving from low- to high-flows, we first consider the annual minimum (daily mean) discharge (Q_0), which we use as a surrogate measure of hydrologic drought. The Q_0 flow represents the lowest recorded mean daily discharge at a gage each year and generally reflects baseflow conditions. It exhibits a strong pattern of trends through the twentieth century. The percentage of the streamgaging stations recording statistically significant trends ranges from a low of 28 percent at 30 years of record to a high of 49 percent at 70 years of record. Significantly, there are many more uptrends than downtrends nationally; that is, the broad pattern is toward increasing annual minimum streamflow. The uptrends exceed the downtrends by 4 to 1 when averaged over all time periods.

Progressing through the lower to middle range of streamflows (Q_{10} - Q_{50}), the pattern that emerges is quite similar to that for the annual minimum discharge; that is, numerous statistically significant trends (25-46 percent of the stations), with many more increases than decreases. However, the situation changes noticeably in the upper half of the discharge distribution. At the Q_{70}

Paper number 1998GL900291.

Table 1. Mann-Kendall trend test results for selected quantiles of streamflow between the annual minimum and maximum.

	Years of Record					
	30	40	50	60	70	80
Beginning year	1964	1954	1944	1934	1924	1914
Ending year	1993	1993	1993	1993	1993	1993
Stations tested	395	395	395	193	70	34
Annual minimum (daily mean) discharge						
No. of significant trends (p≤0.05)	112	177	163	85	34	13
Percent with significant trends	28	45	41	44	49	38
No. with increasing trend	74	145	127	76	32	10
No. with decreasing trend	38	32	36	9	2	3
Annual 10th percentile of daily discharge						
No. of significant trends (p≤0.05)	101	155	143	89	32	12
Percent with significant trends	26	39	36	46	46	35
No. with increasing trend	63	132	117	80	30	8
No. with decreasing trend	38	23	26	9	2	4
Annual 30th percentile of daily discharge						
No. of significant trends (p≤0.05)	109	160	135	81	28	9
Percent with significant trends	28	41	34	42	40	26
No. with increasing trend	76	148	125	79	27	8
No. with decreasing trend	33	12	10	2	1	1
Annual 50th percentile of daily discharge						
No. of significant trends (p≤0.05)	98	174	116	82	27	10
Percent with significant trends	25	44	29	42	39	29
No. with increasing trend	76	167	113	81	26	9
No. with decreasing trend	22	7	3	1	1	1
Annual 70th percentile of daily discharge						
No. of significant trends (p≤0.05)	59	130	64	58	19	6
Percent with significant trends	15	33	16	30	27	18
No. with increasing trend	55	124	61	58	19	6
No. with decreasing trend	4	6	3	0	0	0
Annual 90th percentile of daily discharge						
No. of significant trends (p≤0.05)	43	94	40	20	10	5
Percent with significant trends	11	24	10	10	14	15
No. with increasing trend	18	76	23	19	10	5
No. with decreasing trend	25	18	17	1	0	0
Annual maximum (daily mean) discharge						
No. of significant trends (p≤0.05)	37	53	35	20	9	4
Percent with significant trends	9	13	9	10	13	12
No. with increasing trend	12	31	14	11	5	2
No. with decreasing trend	25	22	21	9	4	2

flow, the number of stations with significant trends drops to 23 percent, averaged over the six time periods. At Q_{90} the average percentage drops to 14 and finally, at the annual maximum flow, only 11 percent of the stations have significant trends. Of perhaps more note is the change in the mix of up- and downtrends. In the low to middle flows there is a clear predominance of uptrends. At the high flows, uptrends and downtrends are roughly equal.

This variation in trends across quantiles is illustrated in Figure 1. The graph covers the period 1944-1993, but the same general pattern is evident in each of the six time periods. There are two important characteristics in the figure. First, the number of increasing streamflow trends is high and approximately equal across the lower half of the flow distribution, but falls sharply across the upper half. Second, downtrends decrease in number from the Q_0 to Q_{50} flow, but increase from the Q_{50} to Q_{100} flow. This pattern indicates that baseflows are increasing (which suggests that drought is decreasing), median or average streamflow is increasing, but annual maximum flows (including floods) are neither increasing nor decreasing. Hydrologically, the nation appears to be getting wetter, but less extreme.

Another aspect of the material contained in Table 1 relates to interdecadal variations in the appearance of trends. Averaging over all quantiles, the highest percentage of streamgaging stations having trends is seen during the 40-year period 1954-93 (36%). High percentages are also evident at the 60-year (1934-93; 34%) and 70-year (1924-93; 34%) periods. However, an average of only 25 percent of the gages have significant trends at both the 50- and 80-year periods, and the lowest percentage of all (20%) characterizes the most recent 30-year period (1964-93). Not sur-

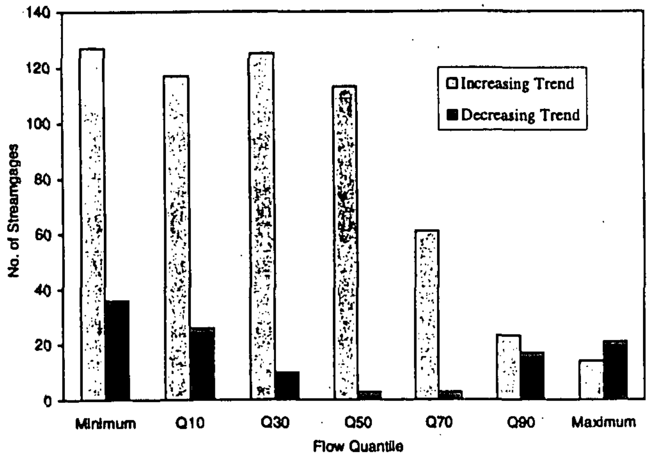

Figure 1. Number of streamgages, out of a total of 395, with statistically significant ($p \leq 0.05$) trends for the 50-year period 1944-1993.

prisingly, trend analysis results are sensitive to the variable characteristics of climatic anomalies occurring in the early and late years of the temporal window being used. For example, between 1944 and 1993 14 stations had uptrends in the annual maximum discharge while 21 stations had downtrends. Between 1954 and 1993, this pattern reversed such that 31 stations were up and 22 were down. Then, between 1964 and 1993, the pattern reversed again with 12 stations recording increases and 25 decreases. There is considerable consistency in the pattern of trends across quantiles and time periods despite the differences in the number of stations exhibiting trends.

We map trend direction and persistence over the six time periods for the annual maximum, median, and minimum flows in Figure 2. There are relatively few trends in the annual maximum flow compared to the annual median and minimum. There are also regionally distinct patterns of streamflow increases and decreases that are consistent across quantiles. Finally, the annual minimum flow has more stations registering trends in three or more time periods. Details of the salient regional features follow.

A broad mix of up- and downtrends in the Q_{100} flow are scattered across the eastern half of the United States, while most of the stations with trends in the western U.S. record decreases. Regionally coherent decreases were most notable in the Pacific Northwest and in the Southern Plains. Considerably more regional coherence is apparent in the trends at the median flow. This part of the discharge regime is characterized by a broad area of uptrends that stretches from the New England to the Lower Colorado water resources region, and that includes the Mid-Atlantic, Ohio, Tennessee, Upper and Lower Mississippi, Texas-Gulf, Rio Grande, and Great Basin water resources regions. Decreasing median flows are most prevalent in the Pacific Northwest and Northern California, and in parts of the Southeast.

Trends in annual minimum flows are nearly identical to those in the median with respect to direction. The differences are primarily in the number of periods when a station exhibits a trend. Many more stations, especially in the Far West, have trends in multiple time periods at the Q_0 level. In the aggregate, most of the nation's water resources regions are experiencing discharge increases at flows below the annual maximum (and actually below the upper quartile, Q_{75}). The only regions exhibiting systematic decreases are the Pacific Northwest, Northern California, and parts of the Southeast; and these decreases are evident at all flow quantiles.

Discussion

Although the specific causes of these variations are not simply and immediately explained, their broad spatial consistency is sufficient to suggest some systematic cause or causes. For example,

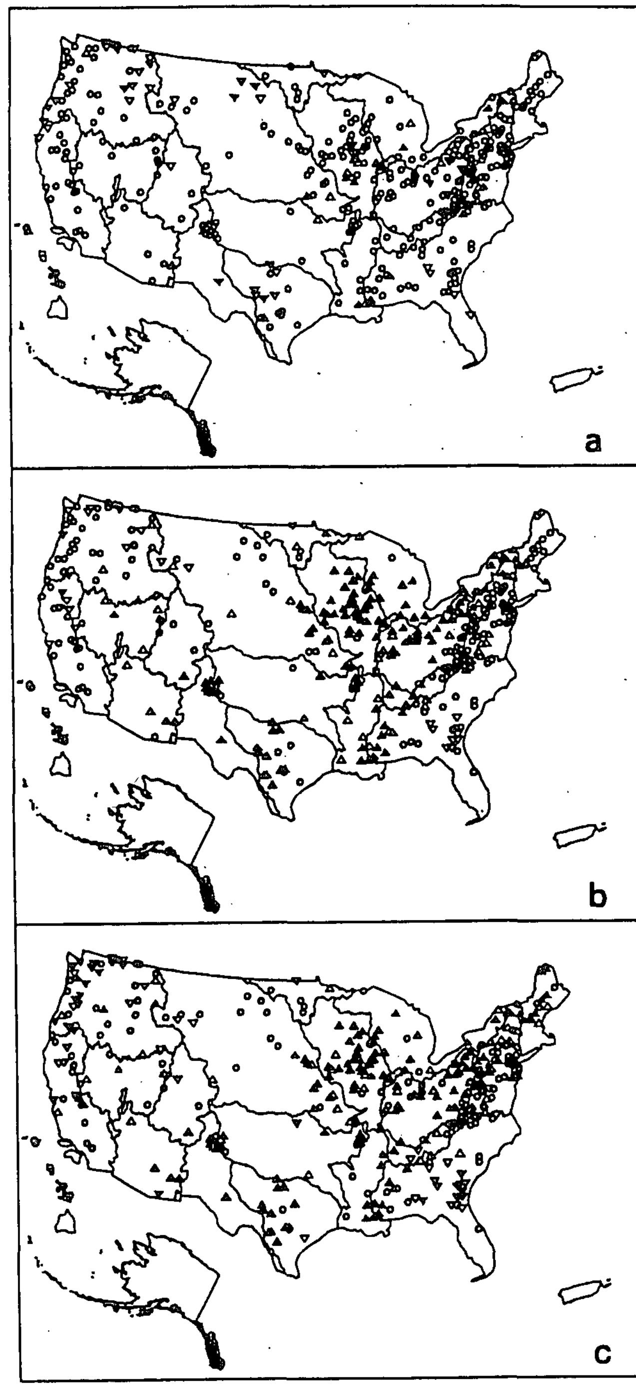

Figure 2. Trends ($p \leq 0.05$) in (a) annual maximum daily, (b) annual median daily, and (c) annual minimum daily discharge in relation to U.S. water resource regions. Upward-pointing triangles indicate increasing discharge, downward-pointing decreasing. Solid triangles (▲) denote stations exhibiting a trend in 3 or more time periods shown in Table 1; gray-shaded triangles (▼) denote a trend in 2 time periods; open triangles (Δ) denote a trend in 1 time period; and an open circle (o) denotes no trend in any time period.

the increases observed in the northeastern quarter of the nation could be associated with precipitation patterns linked with the recent and persistent high index phase of the North Atlantic Oscillation (Hurrell, 1995; Hurrell and van Loon, 1997). The decreases in the Pacific Northwest, especially given the opposing increases in the Southwest, may reflect decadal-scale variations in the tropical and North Pacific Ocean (Dettinger and Cayan, 1995; Graham, 1994; Latif and Barnett, 1994). Opposing climatic and hydrologic anomalies between the Pacific Northwest and the Southwest are well documented as occurring in conjunction with various North Pacific atmospheric circulation modes (Lins, 1997; Cayan and Peterson, 1989).

Climate model simulations associated with increasing atmospheric CO_2 have been interpreted (e.g. Houghton *et al.*, 1996) as indicating an intensification of the hydrologic cycle. This is generally translated to mean more extreme hydrologic events such as floods and droughts. One recent analysis of observed data appears to lend some support to these simulations by indicating that, "at least within the United States--the proportion of total precipitation contributed by extreme, one-day events has increased significantly" during the twentieth century (Karl *et al.*, 1995).

We suspect that our streamflow findings are consistent with the precipitation findings of Karl and his collaborators (1995, 1998). The reported increases in precipitation are modest, although concentrated in the higher quantiles. Moreover, the trends described for the extreme precipitation category (>50.4mm per day) are not necessarily sufficent to generate an increase in flooding. It would be useful to know if there are trends in 24-hour precipitation in the >100mm and larger categories. The term "extreme," in the context of these thresholds, may have more meaning with respect to changes in flood hydrology.

What, if anything, do our results imply for the hypothesis that increasing atmospheric CO_2 will lead to an enhanced hydrologic cycle and, therefore, more floods and droughts? This is a more problematic issue, and one on which current climate modeling studies may soon be able to shed some light.

Acknowledgments. We thank K. Wahl, K. Potter, and S. Burges for thoughtful reviews. Special thanks also to S. Hostetler for many critical comments and numerous insightful discussions.

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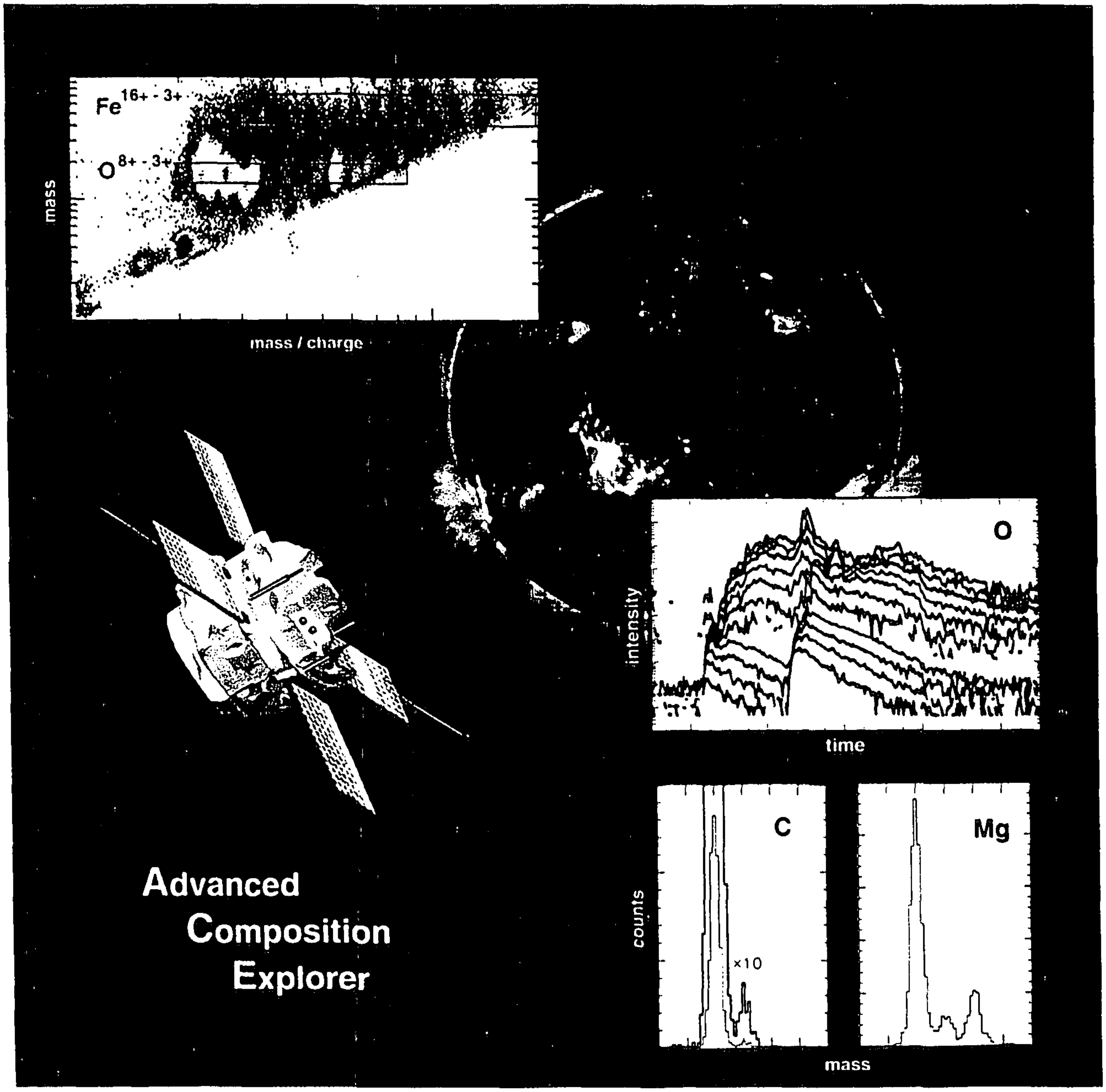
(Received November 6, 1998; revised December 2, 1998; accepted December 3, 1998.)

Geophysical Research Letters

JANUARY 15, 1999
VOLUME 26 NUMBER 2
AMERICAN GEOPHYSICAL UNION



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Highlights of This Issue

Geophysical Research Letters, January 15, 1999

ACE offers insights into particle sources: Special section

The special section in this issue features eight papers that report new results from NASA's Advanced Composition Explorer (ACE), now in orbit about the inner Lagrangian point, L1. Launched in August 1997, ACE carries new high-resolution, high-precision instrumentation designed to measure the elemental, isotopic, and ionic charge-state composition of heavy nuclei in the solar wind, solar energetic particles, and galactic cosmic rays. Two large solar particle events occurred shortly after the launch of ACE.

The energetic particle composition of 6 November 1997 was particularly surprising, exhibiting significant mass-dependent fractionation effects. Four papers examine this event: **Mason et al. [141]; Mobius et al. [145]; Cohen et al. [149]; Leske et al. [153]**. Isotope abundance ratios such as 13C/12C, 22Ne/20C, and 26Mg/24Mg were approximately twice that typical of solar system values, suggesting an acceleration (or other fractionation) process that is very sensitive to the ionic charge-to-mass ratio. Data from ACE shows that the ionic charge states of Mg, Si, and Fe in this event increase with increasing energy, suggesting that the source of higher-energy nuclei is millions of degrees hotter than typical coronal temperatures (~1 million degrees). Several of these authors conclude that more than one acceleration process may have been present in the November event.

Three papers deal with a coronal mass ejection (CME) observed on May 2–3, 1998. This event contained the most unusual ionic abundances observed to date in the solar wind. **Gloeckler et al. [157] and Skoug et al. [161]** report an unusually large and prolonged enhancement of He^{+}, with an abundance comparable to that of He^{++}, along with enhanced 3He. The charge state distribution of Fe ranged from Fe^{+3} to Fe^{+16}, indicating source conditions with temperatures ranging from very cold (~100,000 degrees) to very hot (several million degrees). The presence of Fe^{+3} and other low charge states such as O^{3+}, N^{3+}, and C^{2+}, not observed to date in the solar wind, suggests the injection of cold, solar-prominence material. In contrast to the charge state anomalies, **Wimmer-Schweingruber et al. [165]** report that the isotope ratios of Mg and Si in this event were typical of those observed in the solar wind. **Haggerty et al. [169]** report on a study of energetic proton events observed by ACE and another spacecraft while both were upstream of the Earth's bow shock. The timing of events observed with spacecraft >80 Earth radii apart is difficult to understand using conventional models for these "magnetospheric upstream" events.

Ozone decline continues at the antipodes

Monthly average values of the ozone column for February, March, and April 1991–1998, measured with a UV-visible zenith spectrometer at Thule, Greenland, indicate a decreasing trend in the springtime. Measurements are not only low but also marked by high interannual variations when the polar vortex extends over Thule. Noting that the daily ozone values are strongly dependent on whether Thule lies inside or outside the vortex, **Andersen [193]** reports that in March 1995 and March 1996, when the polar vortex was above Thule, decreases of about 150 DU in the ozone columns were observed. In a separate study, **Connor et al. [189]** report a record-low annual mean value of total ozone (294.5 DU) at Lauder, New Zealand, in 1997. They suggest that the low ozone values observed that entire year may be due to a long-term decline in column ozone.

Ocean recirculation influences tracer patterns

The deep ocean acts as a long-term reservoir for the climate system with the cold waters from the deep-water formation sites traveling from high to low latitudes in the deep ocean. The chemical signature of these waters provides an indicator of the age since the deep water was formed, i.e., the time the water was last in contact with the atmosphere and tagged with "tracers" such as tritium and chlorofluorocarbons. **Lozier [219]** discusses the Deep Western Boundary Current in the North Atlantic and shows that the structure of the recirculations in the deep ocean can help interpret the observed transient tracer patterns. At depths where the recirculation extent is greatest the tracer amount is found to be the smallest. Realistic interpretations of water mass transit times can be made only if estimates of tracer age take into account deep ocean circulation features, the author concludes.

Hydrologically speaking, the U.S. gets wetter

Streamflow is the water that flows in a stream channel, especially its volume and rate of flow. **Lins and Slack [227]** analyze a U. S. Geological Survey compilation of 1944–1993 daily mean discharges from 395 stations in the coterminous United States for trends in the streamflow distribution and for examining how the streamflow regime has changed over the discharge system. They report that the country appears to be getting wetter with time, but less extreme. Streamflow has increased across the country, except for parts of the Pacific Northwest, Northern California and parts of the Southeast where statistically significant decreases occur.

Cover. *New solar wind and solar energetic particle data are obtained from NASA's Advanced Composition Explorer (ACE). The solar image (SOHO/EIT) was taken during a coronal mass ejection observed by ACE. Top left: Ionic charge states for a coronal mass ejection indicate source temperatures ranging from ~100,000 ° to several million degrees. Right, top: Energetic oxygen nuclei (at 11 energy intervals) show the evolution of the coronal mass ejection. Right, bottom: Isotopes of carbon and magnesium show significant mass-dependent fractionation. (See the special section on ACE, this issue.) (Cover art by T. H. Zurbuchen with acknowledgments to B. J. Thompson.)*

13

Spatial Variation in Armouring in a Channel with High Sediment Supply

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ABSTRACT

Recent advances in our understanding of the origin and function of armouring in gravel-bed rivers have not addressed the role of non-uniformity and unsteadiness of flow. These flow attributes have important influences on both the surface and subsurface bed material size distributions which are observed at low flow, from which we commonly make inferences concerning bedload transport at high flow.

Bed armouring, measured as the ratio of surface to subsurface bed material grain size, is highly variable spatially in a channel in which past and present bed aggradation indicates that the sediment supply has exceeded the transport capacity. Alternate bar topography induces strong variations in boundary shear stress, especially at low flow. The resulting winnowing of fine sediment from zones of high stress, such as riffles, and its deposition as thin sheets in zones of low stress, such as pools, produce wide variations in armouring. Linked winnowing and deposition of fine sediment in each bar-pool sequence creates pronounced, local, streamwise sorting by grain size.

Streamwise sorting can lead to pronounced apparent size-selectivity in bedload transport during subsequent rising stages. The relatively fine bedload transported during initial rising stages can originate from unarmoured deposits of fines, where all particle sizes present on the bed surface may be nearly equally mobile. These surfaces are devoid of larger particles, however, that appear in the bedload only when coarser armoured surfaces become more widely entrained.

13.1 INTRODUCTION

In the past decade importance advances have been made in our understanding of bedload transport over mixed-size gravel beds and, more specifically, the fractional transport rates of grain sizes in relation to their abundance in the bed surface and subsurface. The underlying assumption of theoretical approaches

Dynamics of Gravel-bed Rivers. Edited by P. Billi, R. D. Hey, C. R. Thorne & P. Tacconi

(Gessler, 1971; Parker & Kingeman, 1982; Wiberg & Smith, 1987; Andrews & Smith, Chapter 3 of this volume) and interpretations of field data (Andrews, 1983; Carling, 1989; Komar & Shih, Chapter 5 of this volume) is that under steady or quasi-steady flow conditions bedload transport rates and grain-size distributions are in equilibrium with both the hydraulic forces and the structure and grain-size distribution of a uniform bed. The same assumptions have also been the basis for laboratory experiments (Parker, Dhamotharan & Stefan, 1982; Wilcock & Southard, 1988; Kuhnle, 1989; Diplas & Parker, Chapter 15 of this volume). Although understanding equilibrium bedload transport for these relatively simple cases forms the foundation for further progress, natural channels are characterised by their non-uniformity and unsteadiness in flow. It is important to determine, therefore, how the spatial and temporal variability of a natural river affect processes observed or modelled in a local area of the bed.

The texture of channel beds is usually observed when much of the surface is out of water, or at least visible. Such observations only partially show how previous flows have modified the bed. As the flow varies over a channel with non-uniform bed topography, such as that typically produced by bars, local variability occurs in both the direction of sediment transport and the magnitude of the boundary shear stress. Some parts of the channel may continue to supply sediment to be transported, while others become sites of deposition. Non-uniformity in sediment transport leads to the wide variations in the degree of armouring that have been observed to occur locally on a streambed (Mosley & Tindale, 1985; Maloy, 1988; Church, McLean & Wolcott, 1987). The degree of armouring is the coarseness of the armour layer relative to that of the underlying bed material. In this chapter "armour layer" denotes the coarse surface layer of bed particles which is mobile during annual floods, and whose size range greater than 4 mm is completely represented by subsurface material.

The purpose of the study described here was to investigate the spatial variation in the degree of armouring and its relation to channel topography. We selected Redwood Creek for the study because it has a large in-channel supply of bedload and because we expected variations in armouring to be high and most of the bed surface to have been active during recent high flows.

13.2 REDWOOD CREEK

Redwood Creek drains a 720 km^2 basin in north coastal California, USA (Figure 13.1). Streamflow, sediment supply and transport rate, channel changes, and land-use history are well documented (Janda, 1978). The basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. Total basin relief is 1615 m; average hillslope gradient is 26%. For much of its 108-km length Redwood Creek flows along the trace of the Grogan Fault, which juxtaposes two distinct bedrock types. The east side of the basin is mostly underlain by unmetamorphosed sandstones and siltstones of the Mesozoic Franciscan Assemblage, whereas the western side is mostly underlain by a quartz–mica schist. Both rock units have been deformed by numerous fractures and shear zones. The rock incompetence due to this deformation, coupled with high rainfall and steep terrain, contribute to the high erodibility of the catchment.

Annual sediment yields from Redwood Creek are higher than those from other rivers in the US that do not drain active volcanoes or glaciers. Water discharge records (since 1955) and sediment discharge records (since 1970) are available for five US Geological Survey (USGS) gauging stations in Redwood Creek (Figure 13.1). Sediment discharge is strongly flow-dependent and a large proportion of the annual sediment load is transported during infrequent, high-magnitude events. The estimated yield of suspended and bedload sediment from 1945 to 1980 was 2480 t/km^2 per year at South Park Boundary and 2100 t/km^2 per year at Orick (USGS, written communication, 1981). Bedload constitutes 10–30% of the clastic load. Since 1980 sediment loads have decreased to 1190 and 920 t/km^2 per year at the two stations, respectively, primarily due to mild winter storm seasons.

Logging and road construction since about 1950 have contributed greatly to the basin's high sediment yields. Early aerial photographs taken in 1936 and 1947 show that the basin was covered by old-growth redwood and

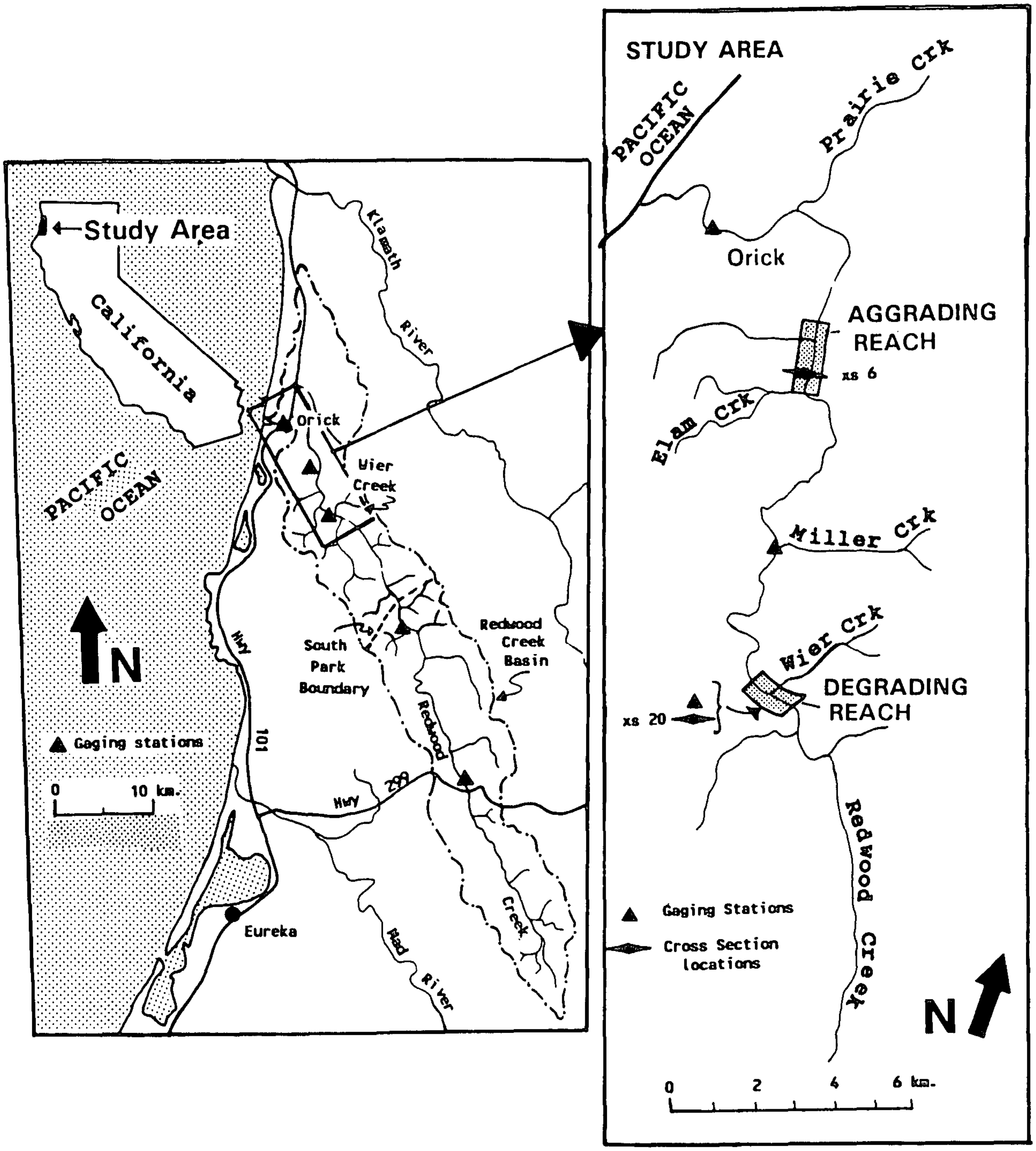


Figure 13.1 Location map showing Redwood Creek, aggraded and degraded study reaches, and five gauging stations

Douglas fir forests with only a few areas of grassland. Redwood Creek was narrow and sinuous in most reaches, and bordered by a thick canopy of trees over much of its length. Timber harvesting began in earnest in the early 1950s. By 1978, 81% of the old-growth coniferous forest had been logged (Best, 1984) and thousands of kilometres of logging roads had been built. Erosion rates during the period of accelerated timber harvesting (Janda, 1978) were about 7.5 times greater than the natural rate estimated by Anderson (1979).

13.2.1 Channel-bed aggradation and degradation

Widespread channel-bed aggradation has occurred since 1964 in response to large floods and a destabilised landscape. Large floods occurred in the Redwood Creek basin in 1861, 1890, 1953, 1955, 1964, 1972, and 1975, but accelerated erosion and channel response was not substantial before the flood of 1964. From 1954 to 1980 a total of 30.5×10^6 tonnes of sediment entered Redwood Creek, mostly from streamside landslides (debris slides, streambank failures, forested block slides, and earthflows) and fluvial erosion originating on unpaved logging roads (gullies, stream diversions, failed stream crossings) (Kelsey *et al.*, 1981; Weaver, Hagans & Popenoe, 1992). Most of the sediment was input during the floods of 1964, 1972, and 1975. The 1964 flood was especially damaging. Even though the peak flow was not exceptionally high (recurrence interval of 50 years; Coghlan, 1984), the flood resulted in widespread streamside landsliding, channel aggradation (up to 7 m) and widening (Madej, 1992). Further floods of 1972 and 1975 resulted in additional aggradation in the downstream third of Redwood Creek.

Channel-stored sediment has continued to be a major source of sediment to downstream reaches. Of the total sediment eroded from 1954 to 1980, 31% was deposited in the channel and on floodplains; little sediment was stored on the steep hillslopes of the basin. From 1964 to 1980, 1.8×10^6 t of sediment was eroded from the channel bed in the upstream two-thirds of Redwood Creek and redeposited in large part in the downstream, lower-gradient reaches (Madej, 1992). Annual surveys since 1973 of 60 channel cross-profiles show that the 1975 flood (recurrence interval 25 years) caused the upstream third of the channel to degrade as much as 1.3 m, while the last 25 km of channel aggraded by as much as 1.5 m (Varnum & Ozaki, 1986). Since 1980 the upstream reach has stabilised at its pre-1964 level, a middle reach continues to degrade, and the last 16 km of channel either continues to aggrade or remains at an elevated level. Thus, the effects of high sediment input upstream have been felt downstream for decades.

13.2.2 Study reaches

We selected two study reaches, one showing recent degradation (Figure 13.2a), and the other, 12 km farther downstream, showing recent aggradation (Figure 13.2b). Although the upstream reach is actively degrading, stressed redwood trees rooted close to the present channel suggest that it has yet to scour down to its pre-1964 level. The reaches thus provide two case studies of armouring in channels with contrasting sediment supplies relative to capacity although, compared to many gravel-bed channels, sediment supply in both reaches is high. Both are straight, alluvial reaches at least 15 channel-widths in length and have similar channel characteristics (Table 13.1). Each reach begins and ends at a riffle crest and has well-developed alternate bars and pool-riffle sequences.

In 1988 field work commenced in the aggraded reach, and in 1989 in the degraded reach. Peak flows during 1988 and 1989 measured at a gauging station 5 km downstream of the lower study reach were 431 and 606 m^3/s, respectively (recurrence intervals of 1.3 and 1.7 years). These moderate flows caused only minor channel modifications, but were still capable of transporting considerable amounts of bedload. Annual bedload yield at Orick was similar in the two years being 56 500 t in 1988 and 55 300 t in 1989.

13.3 FIELD METHODS

13.3.1 Mapping of surface grain size and channel topography

The channel bed in both study reaches showed distinct spatial variation in bed surface texture. In order to map the spatial distribution of bed surface grain size and

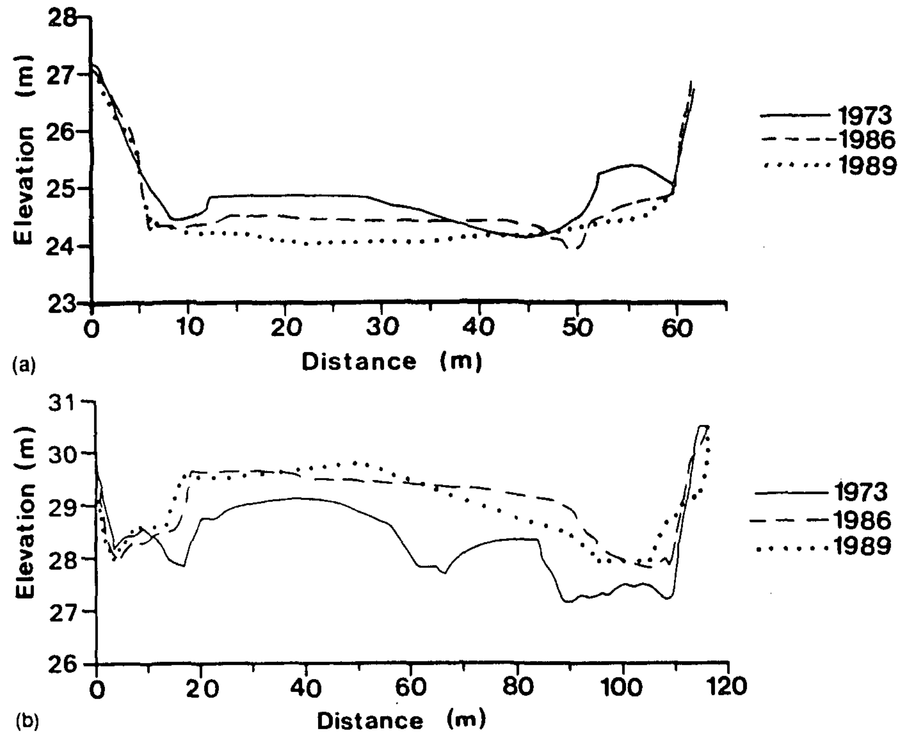


Figure 13.2 (a) Cross-section 20 of Redwood Creek showing a general lowering of the gravel bar surface and thalweg from 1973 to 1989. This scour is typical of the degraded reach. (b) Cross-section 6 of Redwood Creek showing both the gravel bar surface and thalweg at higher elevations in 1988 than in 1973. This pattern of elevated channel beds is typical of the aggraded reach

Table 13.1 Characteristics of study reaches

	Reach	
	Degraded	Aggraded
Drainage area (km^2)	523	605
Bankfull discharge (m^3/s)	370	430
Bankfull width (m)	60	110
Bankfull depth (m)	2.2	1.9
Channel gradient (m/m)	0.0026	0.0014
Length (m)	1284	1670
Sinuosity	1.09	1.03
D_{50} bed surface (mm)	22	15

to sample bed material efficiently, we stratified the bed into recognisable areas whose bed-surface grain-size composition fell into certain predetermined grain-size ranges, which were arbitrarily chosen to represent common grain-size ranges observed on the bed surface of both reaches. Individual mapped areas are referred to as facies; each facies representing one of the three or four facies types defined by a range of grain size. We delineated facies boundaries based on a visual estimate of the D_{75} of the surface particles, and then stratified individual facies by facies type for sampling purposes. In the aggraded reach the definitions of facies types were:

D_{75} < 22 mm = fine-pebble facies;
22 mm < D_{75} < 64 mm = coarse-pebble facies;
D_{75} > 64 mm = cobble facies.

In the degraded reach the same definitions were used, but with the addition of a fourth facies type, bimodal sand, whose bed surface was covered with >25% sand, intermixed with coarse pebbles or cobbles.

Facies were mapped over each reach by staking out and surveying boundaries between facies. In most cases the boundaries between facies were distinct, and mappers independently delineated the same boundaries.

Table 13.2 Number of sampling units in study reaches

	Reach			
	Degraded		Aggraded	
Facies type	No. of units	Percentage of total area	No. of units	Percentage of total area
Fine-pebble	6	27.5	16	30.7
Coarse-pebble	13	43.4	19	52.9
Cobble	8	19.8	15	16.5
Bimodal	5	9.3	—	—
Total	32		50	

Topographic maps were constructed in the aggraded reach using elevation data from facies boundaries and surveying miscellaneous elevations. In the degraded reach elevation data were obtained by surveying a series of cross-sections spaced at intervals of one-third to two-thirds channel-width. Surveys encompassed the channel banks to at least bankfull height, and covered all significant topographic features of the channel bed.

We selected individual facies to be sampled on the basis of probability, proportional to size (in this case, facies area) without replacement. The number of facies sampled was proportional to the total area of the facies type relative to the total channel area (Table 13.2). We gave slightly more weight to sampling the cobble facies type because its size distribution was more variable than the other types. Total areas of each facies type were similar between the two reaches. The coarse-pebble facies, which differed most in area, would have been more similar if bimodal facies in the aggraded reach had been classified separately instead of, in most cases, being included in coarse-pebble facies. Facies types were well represented in both reaches. The bimodal facies type in the degraded reach had the smallest proportion of bed area (9.3%); the coarse-pebble type in the aggraded reach had the largest (52.9%).

13.3.2 Measurements of particle size

Surface and subsurface bed material in each selected facies were sampled systematically. Over each facies we selected 100–150 particles from paced grids (Wolman, 1954), and determined the sieve size range of each particle by passing it through a template with square holes whose sizes ranged at $\frac{1}{2}\phi$ intervals down to 4 mm. The size distribution of material on the bed surface finer than 4 mm was estimated using the size distribution finer than 4 mm of sampled subsurface material, as described below.

Samples of subsurface material from each sample facies were compiled from nine to 12 subsamples taken from points on rectangular grids set up using random starts. Subsamples were taken instead of single large samples because a pilot study had shown that the median grain size of one large sample had a higher variance than that of several smaller samples of equal total weight taken from the same facies. Each compiled subsurface sample totalled about 100 kg. This sample volume was deemed adequate to give reproducible results based on the criteria of Church, McLean & Wolcott (1987) that the largest particle, which usually did not exceed 90 mm in this case, would comprise about 1% of the sample weight.

At each subsample location we removed the surface layer with a flat-bottomed shovel to a depth equal to the D_{90} size of the surface, although for fine-pebble facies we removed to about 2 cm regardless of surface grain size. We then collected a subsample of about 10 kg of subsurface material from a layer about twice as thick as that removed from the bed surface. Subsamples from areas under water were collected from inside a 30-cm-diameter cylinder that had been worked vertically into the bed (McNeil & Ahnell, 1964). Approximately 20% of all subsamples were taken under water.

Samples were air-dried and field-sieved into size classes at $\frac{1}{2}\phi$ intervals down to 11 mm, and weighed. The fraction finer than 11 mm was split, and a 6–8 kg subsample was brought back to a laboratory to be sieved at $\frac{1}{2}\phi$ size intervals down to 1 mm. The fraction finer than 1 mm was disregarded because suspended sediment samples (US Geological Survey, 1970–88) indicated that 1 mm was the approximate upper size limit of suspended sediment, which we assumed did not play a role in armouring processes. Samples taken under water were wet-sieved in the field down to 11 mm, the finer fraction was split and retained for dry-sieving in the laboratory, and wash water containing suspended material was discarded.

13.3.3 Data analysis

Particle size distributions of the surface and subsurface material, expressed as the percentage by weight falling within each size class, were computed for each sampled facies. Sampling of surface and subsurface material by different methods may lead to non-equivalent grain size distributions, but on the basis of the theoretical analysis of Kellerhals & Bray (1971), we assumed that grain-size distributions from grid-by-number measurements (pebble counts) are equivalent to those from sieve-by-weight measurements (subsurface material). This assumption is also supported by the results of an empirical test by Church, McLean & Wolcott (1987).

From these distributions, values of median grain size (D_{50}) weighted by area in each step were computed for each sampled facies, then each facies type and, finally, for the reach as a whole. Similarly, the distributions for each facies were weighted by area to compute mean percentages of each size class for each type and for each study reach, using a method suggested by James Baldwin of the US Forest Service, Berkeley, California. Values of D_{50} for surface and subsurface material and D_{50}(surface)/D_{50}(subsurface), hereafter referred to as the D_{50} ratio, were computed for each facies type and a mean weighted average determined for the study reach.

13.4 RESULTS

13.4.1 Spatial distribution of facies types

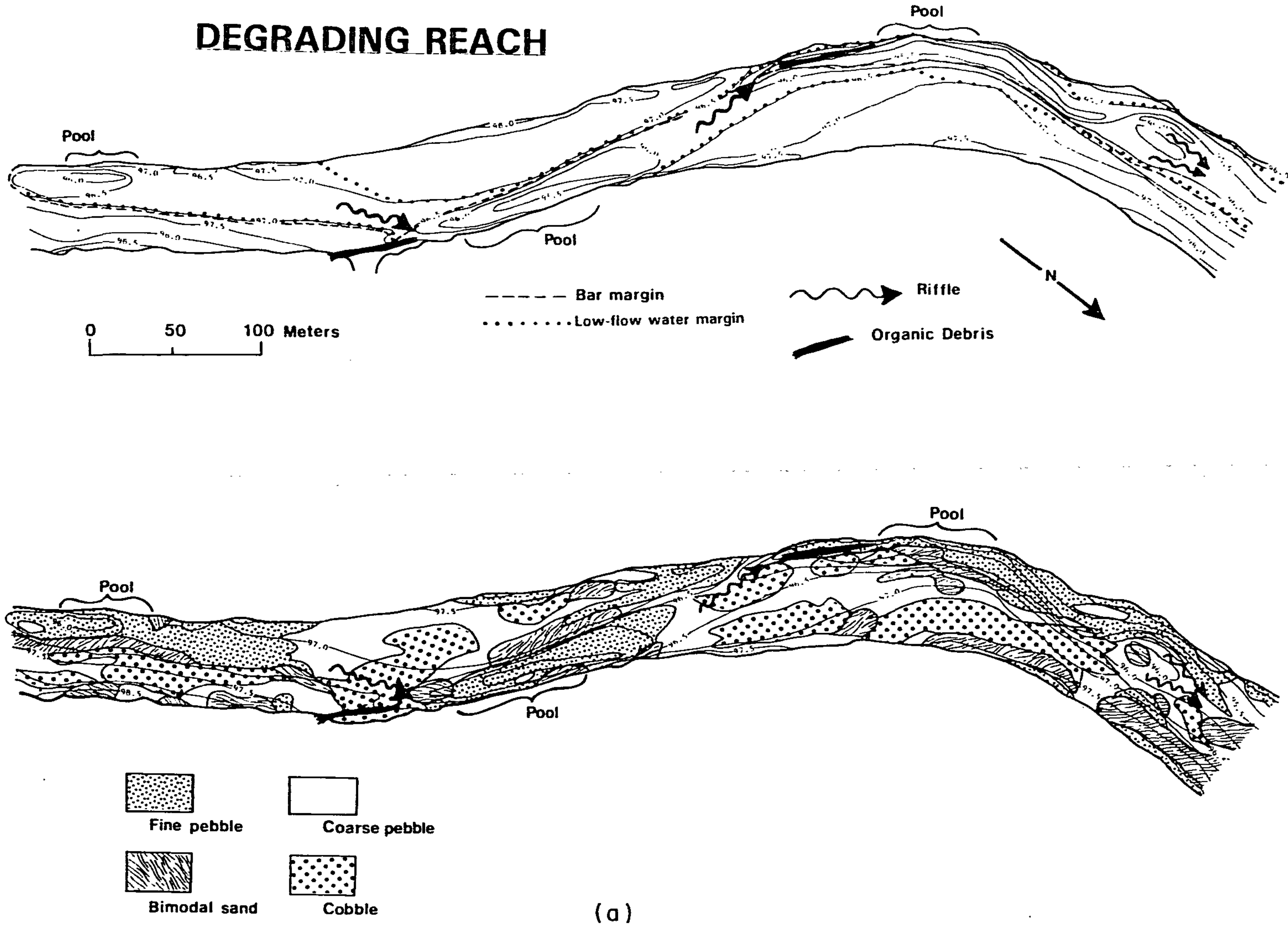
The coarseness of the bed surface correlated commonly with the qualitative magnitude of boundary shear stress at moderate flow when the bed surface was last active. Cobble facies commonly occurred in zones of high or downstream-increasing boundary shear stress where the thalweg crossed a bar and entered the pool downstream. At low flow these areas appeared as riffles and the upstream sub-aerial portions of bar surfaces (Figure 13.3). Fine-pebble facies occurred in zones of low or downstream-decreasing shear stress such as pools, downstream portions of bars, and along streambanks. Bimodal facies in the degrading reach were commonly found near riffle crests. Regarding the wetted channel at low to moderate flow, a downstream repeating sequence was formed in concert with bar-pool sequences: coarse riffles with high boundary shear stress were followed by fine-grained pools with low shear stress.

13.4.2 Size distributions of facies types

Mean surface and subsurface grain size distributions for the reaches as a whole and for each facies type showed distinct patterns (Figure 13.4). All the grain-size distributions (except surface sizes of bimodal facies) were unimodal, spanning sizes from sand to large cobbles. All sizes present in surface material of each facies type were also present in the respective subsurface material. Subsurface grain-size distributions were similar between the different facies, particularly near the coarse end of the size spectrum.

Coarser facies were more strongly armoured than finer ones. With increasing coarseness of facies type, subsurface material became coarser, but not as much so as surface material. Similar results in another channel are reported by Maloy (1988). As quantified by D_{50} ratios (Table 13.3), cobble facies in Redwood Creek were most strongly armoured while coarse-pebble facies exhibited an intermediate degree of armouring approximately equal to that of the channel as a whole.

The coarse limbs of the frequency distributions of surface and subsurface material of the coarse-pebble and cobble facies appeared to be similar. To evaluate this similarity we matched the mode of the surface material to the corresponding frequency of the same grain size of the subsurface material and reduced the remainder of the distribution of surface material by the same proportion. The coarse limbs of surface and subsurface material of the coarse-pebble and cobble facies then corresponded closely, while the fine limbs


DEGRADING REACH
Pool
Pool
Pool
Bar margin
Low-flow water margin
Riffle
Organic Debris
N
0 50 100 Meters
Pool
Pool
Pool
Fine pebble
Coarse pebble
Bimodal sand
Cobble

(a)

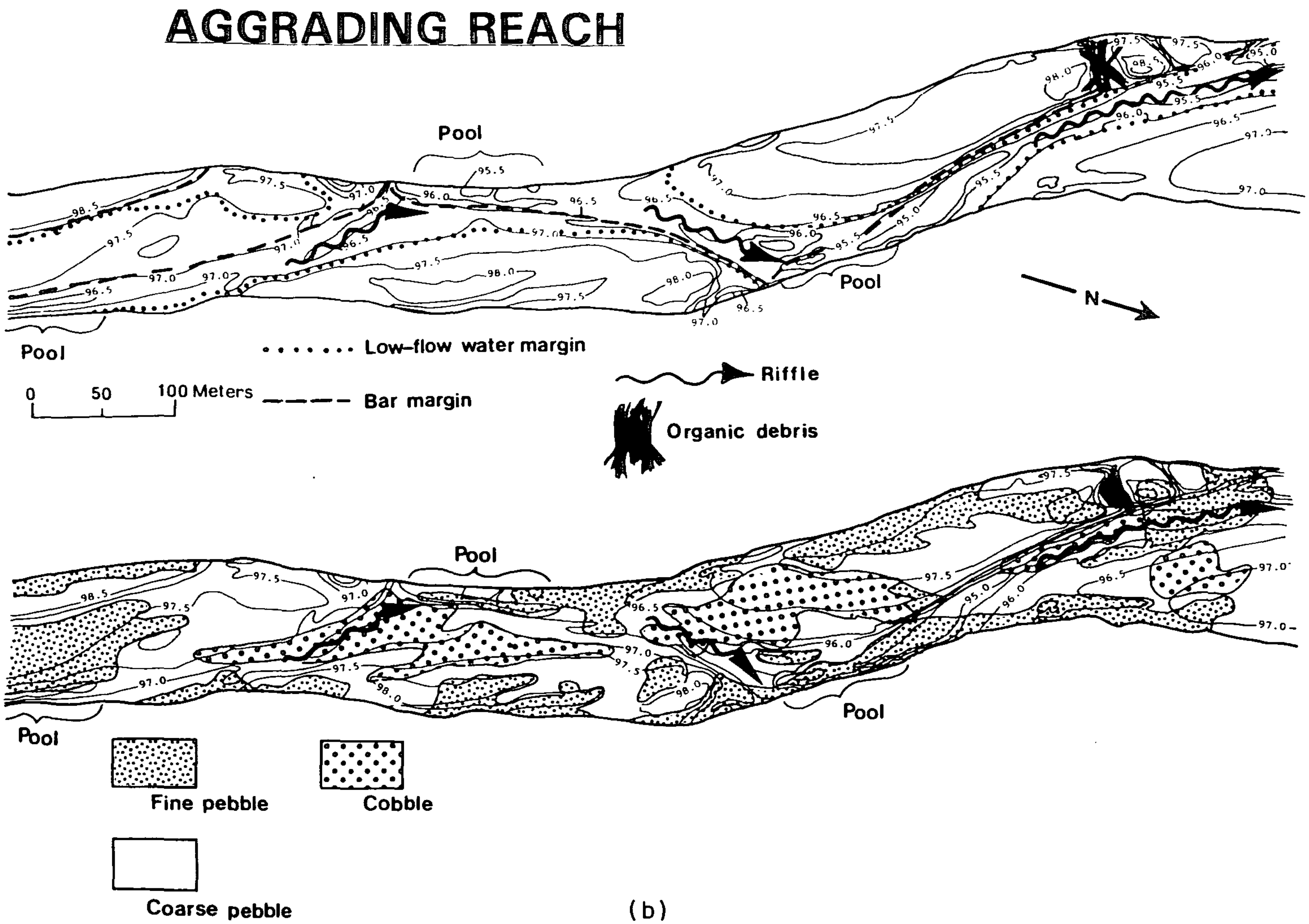


Figure 13.3 Channel bed topography and facies of the degraded and aggraded study reaches, Redwood Creek. Contour interval is 0.5 m

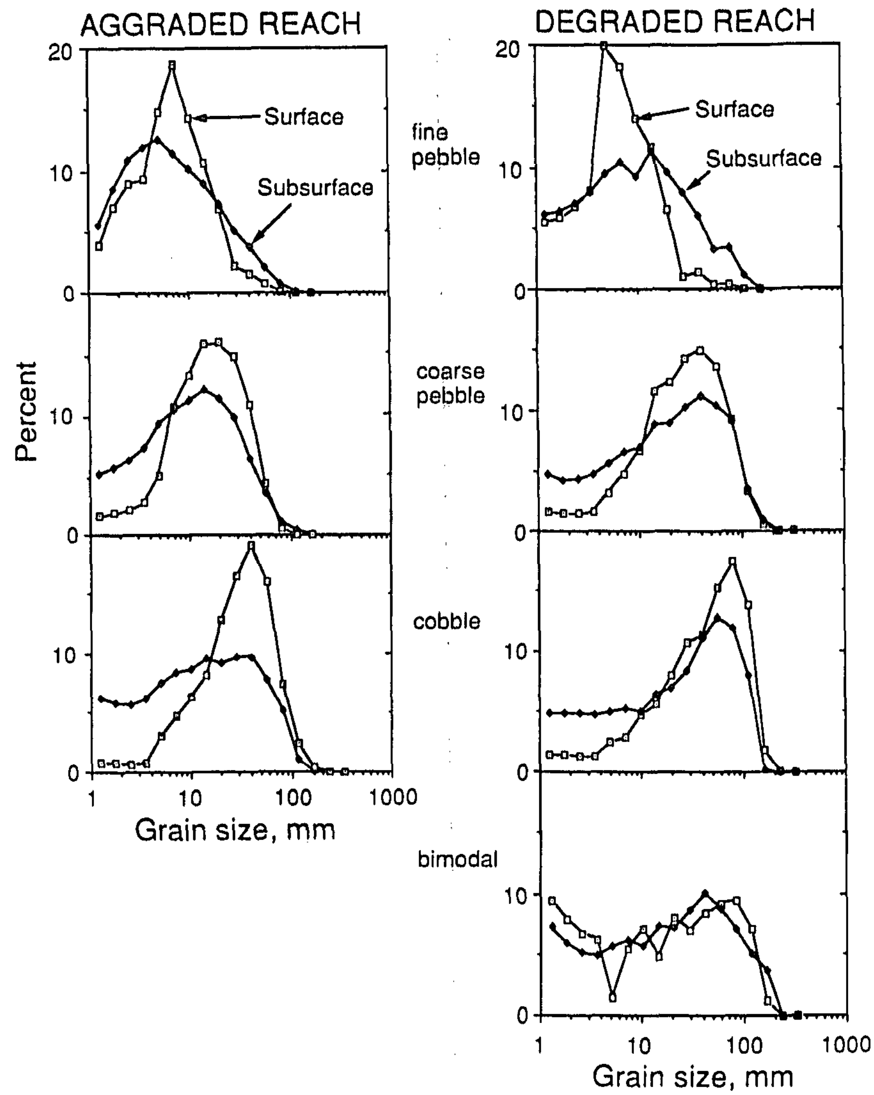


Figure 13.4 Grain-size distributions for surface and subsurface bed material averaged for facies types and for study reaches, Redwood Creek

diverged towards the finer side of the distributions (Figure 13.5). The fine-pebble facies did not display this pattern, and the frequency distributions of the bimodal facies matched without any adjustment of the distribution of surface material. This suggests that the grain-size distribution of surface material of the coarse-pebble and cobble facies could have resulted by winnowing of the finer fractions more abundantly represented in their subsurface materials.

Of all facies types, bimodal facies showed the closest correspondence between surface and subsurface grain-size distributions. The lack of actual bimodality arises from variations in size distribution of the fine mode among the samples from which the average distributions were computed. In the field the surface of bimodal facies gave the impression of an exposure of a horizontal section of streambed, revealing the framework of coarse particles as well as the matrix of

Table 13.3 D_{50} of surface and subsurface material and D_{50} ratios and their respective standard errors (s.e.) for study reaches of Redwood Creek

	Reach					
	Degraded			Aggraded		
	D_{50} (s.e.)		D_{50} ratio (s.e.)	D_{50} (s.e.)		D_{50} ratio (s.e.)
Facies type	Surface	Subsurface		Surface	Subsurface	
Fine-pebble	5.7 (1.0)	10.5 (1.6)	0.68 (0.14)	6.1 (0.7)	6.2 (0.5)	1.05 (0.14)
Coarse-pebble	26.2 (1.5)	19.2 (1.1)	1.44 (0.06)	14.9 (0.6)	9.7 (0.4)	1.60 (0.09)
Cobble	38.2 (2.6)	24.4 (2.6)	1.66 (0.19)	30.0 (1.3)	13.0 (0.6)	2.45 (0.16)
Bimodal	18.4 (4.1)	22.0 (3.1)	0.96 (0.19)	—	—	—
Weighted average	22.2 (0.9)	18.1 (0.9)	1.23 (0.06)	14.7 (0.4)	9.1 (0.3)	1.57 (0.07)

fine particles.

Fine-pebble facies were also unarmoured and many appeared to be "anti-armoured", that is, having a surface layer finer than the subsurface layer. For example, the D_{50} ratio averaged for the fine-pebble facies of the degraded reach (0.68) was considerably less than unity. Anti-armouring is, however, to some degree an artifact of our method of sampling the subsurface. In scraping away the surface of fine-pebble facies that were thin, we essentially removed those facies — that is, the bedload material that was last transported over that area of bed — and sampled coarser, underlying material. Thin fine-pebble facies were prevalent sub-aerially or in shallow water, where we were able to sample the subsurface. Fine-pebble facies in deep water were commonly thick. Considering these uncertainties, it is perhaps prudent to assume that fine facies have D_{50} ratios no less than unity.

The thickest and most extensive fine-pebble facies, particularly in the degraded reach, consisted of sheets of sand and small pebbles less than 0.5 m thick, that mantled coarser material in the beds of pools (Figure 13.6). These deposits thinned downstream from pool deeps and, approaching riffle crests, graded into bimodal facies and then into coarse-pebble or cobble facies as the large particles covered by fine sediment were increasingly exposed.

In summary, bed material grain sizes and the distribution of boundary shear stress revealed streamwise particle sorting within each bar-pool sequence. During waning flows, sand, gravels, and small pebbles were winnowed from riffles where boundary shear stress was relatively high, resulting in a high degree of armouring. Winnowed material was carried downstream and deposited as thin sheets of unarmoured, fine-grained material over pools, where shear stress was low.

13.5 DISCUSSION

13.5.1 Winnowing and streamwise sorting

Winnowing has a strong influence on the bed surface of Redwood Creek, at least as seen at low to moderate flow when the bed can be readily observed. Although selective accumulation of coarse particles on the bed surface can be responsible in part for surface coarsening, the surface layer of the armoured facies appeared to be depleted in fines rather than being enriched in coarse particles. The largest size of particles in the coarse armour layers of individual facies were also present in the underlying material. The coarser facies types, moreover, exhibited similarities between the coarse limbs of the frequency distributions of surface and subsurface layers. In contrast, the surface of the bed classified as the finest facies type was enriched in fines and commonly consisted of a veneer of fine material overlying a coarser bed. Together, these results suggest that the winnowing of fines from coarse facies and their deposition downstream to form fine-grained facies was largely responsible for spatial variations in armouring observed at low flow. The coincidence of high boundary shear

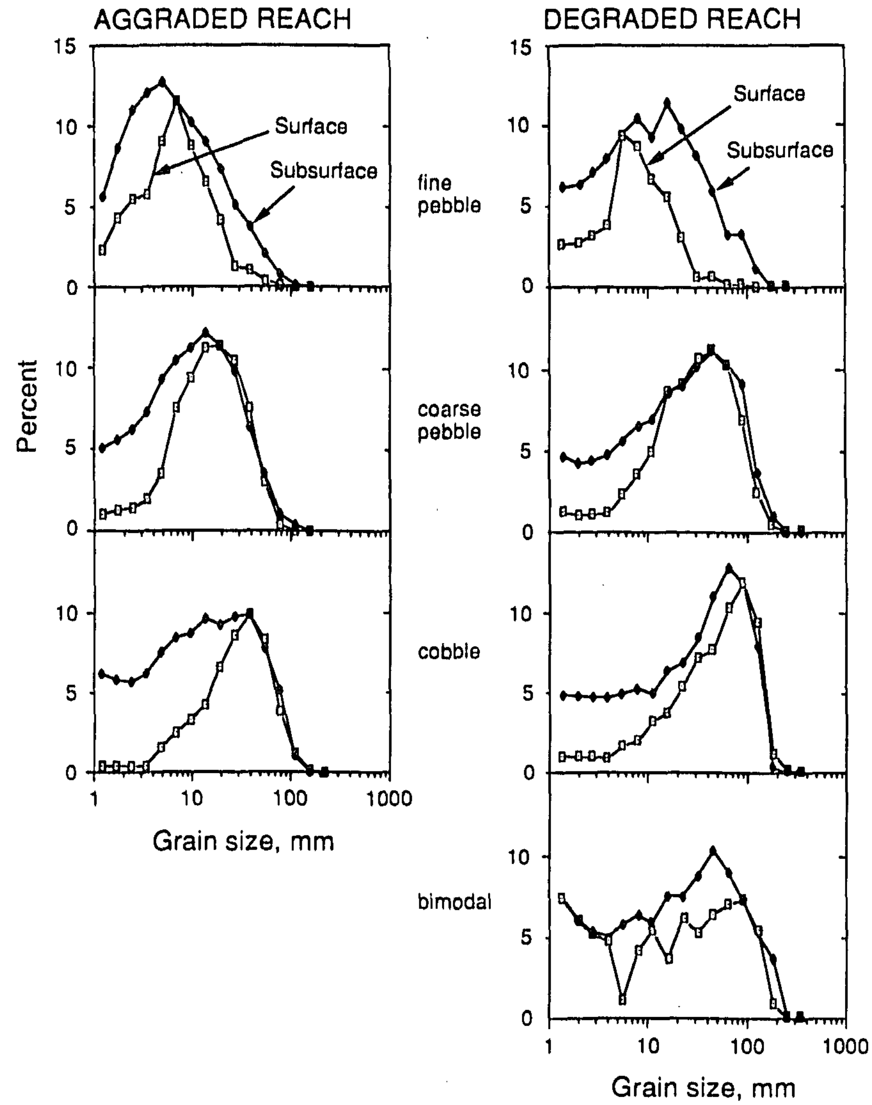


Figure 13.5 Adjusted grain size distributions from Figure 13.4. The frequency of the mode of the surface material was reduced to the value of the frequency of the same grain size of the subsurface material, and the remainder of the distribution of surface material was reduced by the same proportion

stress at low flow with coarse (winnowed) facies and low shear stress with fines-enriched facies is consistent with this interpretation.

In this discussion it is important to distinguish between vertical and downstream winnowing (Parker & Klingeman, 1982). In vertical winnowing, fines are temporarily lost to the subsurface layer; in downstream winnowing fines are carried downstream. As Gomez (1984) points out, vertical winnowing requires that the coarse particles in the surface layer be mobile, while downstream winnowing requires that they be temporarily immobile. Most importantly, downstream winnowing leads to streamwise sorting of bed material, but vertical winnowing does not. The juxtaposition of coarse and fine facies indicates that downstream winnowing of coarse armour layers in Redwood Creek

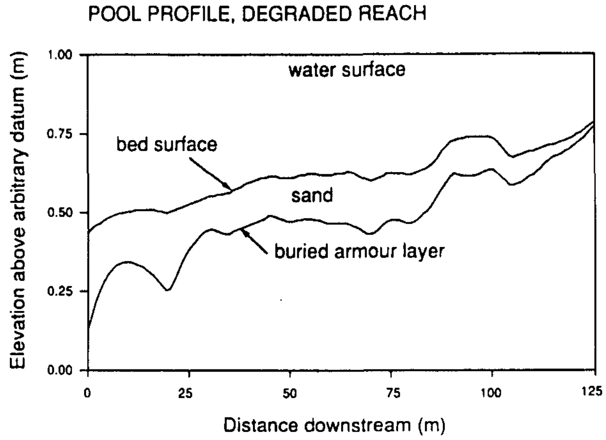


Figure 13.6 Longitudinal profile of the water surface, bed surface, and armour layer buried under fine sediment in a pool of the degraded reach, Redwood Creek. The survey was conducted on 31 August 1989 during low flow

was prevalent during waning stages of flood hydrographs.

13.5.2 The compatibility of equal mobility and size-selective transport

A result of streamwise sorting within each bar-pool sequence in Redwood Creek is that, over most of the bed at low flow, the surface grain-size composition is a product of various degrees of winnowing or deposition of winnowed material during waning flow. These bed surface conditions would not be expected to prevail during high bedload-transporting stages. As a result, bed surface grain size in a local area could not necessarily be used to predict bedload grain sizes or transport rates at that point, at all flows. This is because bedload transport would be a function not only of local bed conditions, but also of those along the sediment transport path leading to that point from upstream. In other words, a simple model of equilibrium between bedload transport and bed surface grain size at a point, which has formed the foundation for theories of sediment transport over mixed-size beds, is not entirely valid for a natural channel such as Redwood Creek.

Streamwise sorting can provide a resolution to a paradox of equal mobility and size-selective *transport*. Theoretical treatments of initial particle motion from a mixed bed (Wiberg & Smith, 1987; Komar & Li, 1988; Kirchner *et al.*, 1990) fail to show conclusively a mechanism for size-selective *entrainment* of particles, because of uncertainties in the magnitude of lift and drag forces, and wide variations in pocket geometry and pivot angles. On the other hand, bedload transport measurements from natural channels can show some degree of selective *transport* over a range of stage (Milhous, 1973; Carling, 1983; Ashworth & Ferguson, 1989; Kuhnle, Chapter 7 of this volume). Selective transport is very pronounced in Redwood Creek. At discharges as low as 5% of bankfull we have observed sand and fine gravel transported as migrating dunes over an armour layer. Bedload samples at high flow (USGS, 1970–88) contain the largest particles that can fit into a Helley–Smith bedload sampler with a 7.6-cm orifice, and cross-sectional changes and painted-rock experiments (unpublished data, Redwood National Park, Arcata) show that all particle sizes represented on the bed surface are transported at high stages. Grain sizes of bedload samples taken over a range of flows could lead one to conclude that there is strong stage-dependent, size-selective *entrainment* from a streambed where a large range of grain sizes are present.

Extrapolation of observations of bedload transport at a point or section to a reach of channel as a whole can be erroneous, however. In Redwood Creek the most mobile sources of bedload at discharges when only sand and fine gravels are transported are fine-grained, winnowed sediment that was deposited in pools during the previous waning stages. These areas are the last to be deposited in and the first to be entrained from. All particle sizes on the surface of these areas may be nearly equally mobile; coarse gravel and cobbles are merely absent. This fine bedload is carried downstream and overpasses the stable armour layer of coarser facies as streaks of moving material that disappear as stage drops and the bed is winnowed. Thus, the apparent degree of size selection in entrainment and transport depends on the part of the bed observed. At rising stages bedload may be first entrained from fine areas that exhibit equal mobility. The initial fineness of bedload arises not from selective entrainment of particles from an overall population with a wide range of grain size, but from streamwise sorting that provides fine, unarmoured areas of the bed that are exceptionally mobile. The resolution of the paradox, therefore, is that equal mobility can coexist with size-selective transport in a channel with streamwise sorting.

13.6 CONCLUSIONS

Wide spatial variations in boundary shear stress in response to varying flow in Redwood Creek have created large spatial variations in the grain sizes of surface and subsurface materials. The bed at low flow, when it is practical to observe armouring of the entire channel, is to a large degree the product of waning flows. Although low flows are too feeble to transport significant volumes of bedload, spatial variations in boundary shear stress near entrainment thresholds enhance heterogeneity in bed texture through size-selective transport and deposition. As general transport ceases fine sediment is winnowed from the bed surface of riffles, where shear stress remains relatively high, and deposited in pools, where shear stress is low. During rising stages the process is presumably reversed with pools switching from being the sink for fine-sediment transport to becoming the source of fine sediment transported over the armoured beds of riffles.

A result of pronounced streamwise sorting in a channel with a large in-channel supply of bedload is that sediment can be entrained from different areas of the bed over a wide range of flow. Collectively, therefore, the channel is highly mobile despite a high degree of armouring in some areas.

The organisation of bed surface texture and boundary shear stress in a natural channel present challenging complications to the prediction of bedload transport. Firstly, predictions employing mean values of hydraulic variables and channel-boundary conditions for the channel as a whole exclude the influence of spatial variations in bed mobility. They can fail, therefore, to predict accurately the onset of bedload transport and transport at moderate stages. Such an approach can also lead to the erroneous conclusion that fine-grained bedload transported at low to moderate stages originates from size-selective entrainment from a uniform bed having a wide range of particle sizes present over the entire bed. Instead, the sediment source is most likely to be highly mobile, fine-grained areas of the bed surface.

Secondly, spatial variations in the bed surface texture measured at low stages may not be representative of those at high stages, when bedload transport rate predictions may be more important. Predictions of bedload transport may be more appropriately based on values of hydraulic and boundary conditions in small unit areas of the bed that are linked along sediment transport paths in such a way as to account for the disequilibrium imposed by discontinuities in sediment transport and the progressive changes in conditions as flow varies.

13.7 ACKNOWLEDGEMENTS

Sue Hilton supervised the data collection and calculated the grain-size parameters. We were assisted in the field by Alice Berg, Scott Bowman, George Cook, Carrie Jones, Mike Napolitano, Vicki Ozaki, Christine Shivelle, Sherry Skillwoman, Stephan Stringall, and Victor Vrell. Laura Leising drafted the facies and topographic maps. Bill Dietrich and Jonathan Nelson provided valuable discussions.

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13.9 DISCUSSION

13.9.1 Discussion by N. R. Jaeggi

Obviously, armouring processes are complicated by the occurrence of alternate bars. The situation described in the paper is thus more complex than an armouring process in the flume with plane bed. However, locally, over a short distance, the process on a bar or in a pool will be the same as for plane bed conditions with same shear stress. The problem is to define the representative shear stress in a complex field situation.

One-dimensional numerical modelling of bed level changes and bedload transport in the Danube (see Chapter 30 in this volume) and in the Alpine Rhine was successful despite the occurrence of alternate bars. In the model a critical shear stress for erosion of the armour layer was used. Assumptions had to be made on form roughness induced by bars at lower flows and shear stress variation over the cross-sections. The validity of these assumptions could be controlled by comparison with surveyed bed level changes.

The Alpine Rhine degrades while bars migrate, so the erosion is about the same on the whole cross-section. In the Danube the bars are fixed by groynes and thus the thalweg tends to incise and the bars tend to form terraces. The terraces formed with about a 4% slope (Ova da Bernina, Switzerland). It would be interesting to know what happened in the degrading reach of Redwood Creek.

13.9.2 Discussion by D. A. Sear

The authors mention the influence of spatial variation in armouring upon the transport and grain size of the bedload. Work on the River North Tyne in the UK supports the idea of topographic control on spatial armouring but also suggests that regard should be made to the distribution of bed compaction.

Figure 13.7 illustrates a dynamic penetrometer survey of bed compaction within a riffle–pool–riffle sequence. A distinct spatial pattern in compaction is evident and can be linked to topography, bed micromorphology and reach hydraulics. Compaction of riffle beds extends into the pool head in association with a region of high shear stress, or jetting. Accentuated levels of compaction also correspond to stable bar forms and to a boulder zone along the right bank of the pool. These areas also exhibit profound bed micromorphology that increases the compaction.

Zones of low compaction, independent of grain size, exist in the pool tail and in the region of low shear stress adjacent to the high-velocity jet. Very little bed structure is apparent within these regions and "anti-armour" is absent.

Under these circumstances the mutual interlock of particles leading to a state of compaction might reasonably be expected to exert a control on the stability of the bed and, therefore, the initiation of sediment transport within the reach which is independent of the surface grain size.

13.9.3 Discussion by P. A. Carling

The authors draw attention to the fact that both winnowing of fine matrix from the interstitial space of a static gravel surface, and selective accumulation of coarse gravel above finer gravels may result in a texturally stratified bed. The fact that a variety of mechanisms may be involved in the process has been remarked upon before (Carling, 1981; Bray & Church, 1982; Gomez, 1984). I would, however, question whether the term "anti-armour" is an appropriate new term, as these latter deposits seem to bear no structural relationship to the underlying deposits and are, apparently, low-flow drapes or veneers (see Carling & Reader, 1982, Figure 8).

The mechanism of selective accumulation is the one most commonly associated with armouring (paving), whereby a dynamic segregation process associated with bed material transport of fine and coarse fractions leads to surface coarsening. In addition, the process is often associated with bed degradation. The result is a surface which is more resistant to entrainment than the parent bed material which underlies it. Commonly, the D_{50} of the armour is some 2.5 times larger than that of the sub-armour (e.g. Parker, Klingeman & McLean,

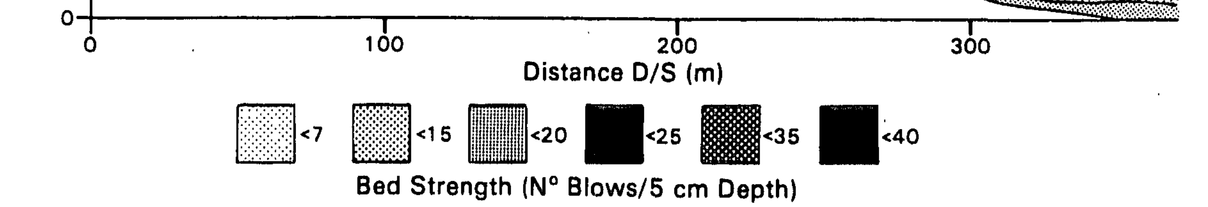

Figure 13.7 Spatial variation in bed compaction within a riffle–pool–riffle section of the River North Tyne, UK. Measurements were made using a Mackintosh Probe dynamic penetrometer. Flow direction is from left to right

1982), but in extreme cases the armour may consist of a pebble layer over-lying sands (Leopold, Wolman & Miller, 1964, p. 209).

In contrast, surface winnowing by traction or suspension of fines does not entail bed degradation, leaves a static coarse framework (see Chapter 15 in this volume) and does not entail the rearrangement of the coarse component of the bed. The resultant coarse surface imparts little in the way of increased bed stability; indeed stability may be decreased by the removal of a previously well-packed matrix.

In view of the current interest in the detailed structure of riverbeds I would welcome the authors' views on whether a variety of segregated surfaces exist, and if it would be useful to develop a more detailed classification.

13.9.4 Reply by T. E. Lisle and M. A. Madej

Sear and Carling rightly state that particle arrangement as well as grain size govern the mobility of bed surfaces under given hydraulic environments. Mapping surface particle arrangements and measuring their effect on entrainment thresholds in the field is problematic at this point, although Sear's penetrometer technique offers a quantitative parameter. Arrangements of coarse particles in armour layers of Redwood Creek vary widely. Although we did not measure compaction as Sear did, we would concur that bed firmness, or particle arrangement, does not always correlate with surface grain size. Some coarse, well-armoured areas are imbricated, suggesting either selective deposition of coarse material or at least reorientation *in situ* of coarse particles as finer particles are winnowed away downstream. Many cobbles on some riffles in the degraded reach lie loosely on the bed and, as Carling suggests, may have been left by winnowing of a well-packed fine matrix, and thereby rendered less stable.

We do not intend to introduce a new term, "anti-armouring". It is used only to refer to an apparent phenomenon that was widespread in fine-grained areas of Redwood Creek and, as Carling warns and we describe, should not imply a contemporary sedimentological relation between a thin surface layer of fines and the underlying coarser bed material.

Jaeggi indicates that detailed measurements of bed topography and bed-surface particle size may not be necessary for practical solutions to sediment transport problems in rivers with alternate bars. Our research in Redwood Creek is intended to increase understanding of effects of non-uniformity and unsteadiness of flow on bedload transport in gravel-bed rivers, and not necessarily to provide new engineering applications.

The bars in Redwood Creek do not migrate downstream because the sinuosity of the channel is commonly bounded by hillslopes. The study reaches were chosen to be straighter than is characteristic of the channel in general. Terraces of recent flood deposits left by channel degradation are absent in the degraded study reach, but do appear upstream, where the channel has degraded more deeply and valley bottoms are wider.

13.10 DISCUSSION REFERENCES

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