

Mad River EIR Technical Supplement
Section 3:
Estimation of Mad River Gravel Recruitment
and
Analysis of Channel Degradation

Andre Lehre
Dept. of Geology and Institute for River Ecosystems
Humboldt State University
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INTRODUCTION

Significance of Gravel Recruitment

Gravel recruitment is the natural resupply of gravel to a channel reach from upstream by bedload transport. It is typically given in tons or cubic yards per year. If average annual gravel extraction is less than or equal to average annual gravel recruitment, then a condition of *sustained yield* exists. If average annual gravel extraction exceeds average annual recruitment, then the gravel resource is being *mined*, or depleted. Such mining commonly leads to undesired effects such as bank erosion or bed degradation downstream. Under sustained yield the channel is more likely to remain reasonably stable. Hence estimation of gravel recruitment is central to any study of the impacts of gravel mining on a channel.

Overview of Mad River Bed Degradation

Over the past thirty years, the bed and bars of the Mad River have in general degraded (lowered) significantly. While this general bed lowering affects the entire channel downstream from the hatchery to the mouth, it is especially obvious in the reach between Blue Lake and the Highway 299 bridge, and has reached the point where it is seriously affecting the Railway bridge, the 299 bridge, and the HBMWD intakes. I list several observations below that indicate the extent of this problem.

- **Blue Lake bridge (Hatchery Road):** Comparison of channel cross-sections surveyed in July 1991 by Andre Lehre and Tom Lisle with original 1982 construction cross-sections shows maximum local bed lowering of 4.5 ft. Mean bed lowering (lowering averaged across the entire channel width) at this site is 1.6 ft.
- **Railway bridge:** The footings of the northern pier of the Railway bridge are virtually completely exposed and appear to be undermined. I was able to thrust a stick 4 -5 feet under the NE corner of the pier without encountering anything solid. A willow growing on the south side of this pier marks a fairly recent position of the old ground surface; the willow's base is now about eight feet above the current bed surface.
- **HBMWD structures:** The HBMWD Ranney collector towers have been increasingly exposed; one tower has had to have two additional lengths of ladder welded on, indicating up to 8 feet of bed lowering. Such bed lowering reduces filtration effectiveness of the collectors. Bed lowering at pump station 6 (which supplies the Samoa mills) has brought the pumps to within 0.5 - 1 foot of sucking air at low water. Cross-sections surveyed for HBMWD indicate mean bed lowering throughout the reach of about 4 - 5 feet since 1960.
- **Highway 299 bridge:** Comparison of channel cross-sections surveyed in July 1991 by Andre Lehre and Tom Lisle with original 1960 construction cross-sections shows maximum local bed lowering of 14 ft under the downstream span of the Hwy 299 bridge. Average bed lowering (across the entire channel width) since 1960 at this site is about 8 ft. CalTrans surveys of the 299 bridge indicate a maximum bed lowering since 1941 of 22 feet on the upstream span. The footings of pier 4 have been exposed and the concreted right bank at pier 5 has been undercut.
- **Highway 101 bridge:** CalTrans surveys of the Highway 101 bridge show maximum downcutting of 17 feet since 1929 on the upstream span and 8 ft since 1957 on the downstream span.
- **Tributary creek downcutting:** Near their entrances to the Mad River, Lindsay and Mill Creeks have cut down 8 to 10 feet since bridges were constructed across them. The eastern footings of the Lindsay Cr. bridge are completely exposed. Large rocks have had to be emplaced below the Hwy 299 Mill Cr. crossing to prevent undercutting and to allow fish passage.

General Causes of Bed Degradation

The gravel resource stored in any reach of a river can be visualized as a bank account. The capital in the account is contained in the bed, the bars, and the banks along the channel. Deposits are made naturally into the account as new gravel is brought in (recruited) from upstream. Natural withdrawals from the account occur as gravel is transported downstream out of the reach by the river. Checks are written on the account as gravel is extracted by man. As with any bank account, if deposits exceed withdrawals, the capital in the account will increase, that is, the river will raise its bed (aggrade) and build up the bars. On the other hand, if withdrawals and checks exceed the deposits, the balance in the account will diminish; in the case of a river, this means lowering of the bed (degradation) and widening of the channel.

The river as a whole can be looked at as a string of serially linked adjacent bank accounts (reaches), whereby the natural withdrawals (outflows) of bed material from each account provide the natural deposits (inflows) to the account immediately downstream. Thus deposits to any downstream account reflect the cumulative effects of all upstream actions. In particular, if upstream reaches intercept most of the natural gravel recruitment (i.e., the cash flow to downstream accounts is reduced), deposits to reaches farther downstream can only come by reducing the capital in the intervening accounts, i.e., by eroding the bed and banks.

The persistent general bed lowering observed in the lower Mad River has been caused by 1) low rates of recruitment of new bed material from upstream because of a succession of dry years with low peak flows, combined with 2) substantial extractions of bed material from the channel by gravel consumers. In order to determine the exact contributions of each cause to the observed bed lowering we would need for several years: 1) measurements of the rate of transport of bed material into, through, and out of the reach; 2) accurate and complete records of the amounts of gravel extracted yearly; and 3) repeated detailed topographic maps and cross-sections of the channel to assess changes in storage. None of these exist. We can, however, use available hydrologic and engineering data to make crude estimates of new gravel recruitment and compare these with past and proposed extractions, and with observed degradation. This crude *sediment budget* should allow at a minimum an order-of-magnitude assessment of the effects of gravel extraction on the river.

Data Sources

Time and money limitations on this study made it impossible to collect new data for this report. Instead, we have had to rely on whatever hydrologic, geologic, and engineering data was already available. Much of this data is scanty or incomplete; it is, however, all that we have, and we must make the best of it despite its shortcomings. Table 3.1 summarizes the sources and type of data we used.

ESTIMATION OF GRAVEL RECRUITMENT

General Approach

Because the estimate of average yearly gravel recruitment is so crucial to analysis of the effects of gravel mining on a river, it is desirable to estimate it using several different, more-or-less independent techniques. At the best, all will yield similar values, suggesting that the estimate is reasonably good. At the worst, the different estimates can be used to put likely upper and lower bounds on the true value. The approaches used depend largely on what data are available. For the Mad River I estimated annual recruitment using:

- 1) Brown's (1975) bedload rating curves, based on actual bedload measurements;
- 2) the Ackers-White, Bagnold, Einstein-Brown, Meyer-Peter, and Meyer-Peter-Müller bedload equations;
- 3) the mean ratio of bedload to suspended load in typical gravel-bed streams.

Each of these methods is described below.

Table 3-1 -- Data Used in Gravel Recruitment and Channel Degradation Study

Type of Information	Site	Dates	Source
Daily flow data	Mad R at Arcata (Hwy 299) Mad R near Blue Lake (just above Hatchery) Mad River near Kneeland (near Butler Valley)	1960-92 1972-73 1965-73	USGS USGS USGS
Bedload discharge measurements Bedload particle-size measurements	Mad R at Arcata Mad R near Blue Lake Mad River near Kneeland	1971-73 1972-73 1972-73	USGS; Brown, 1975 USGS; Brown, 1975 USGS; Brown, 1975
Bed material surface size distribution	Mad R at Arcata Mad River at Hatchery	1972 1989	USGS Lehre class
Hydraulic geometry (width, depth, velocity) measurements	Mad R at Arcata Mad R near Blue Lake Mad River near Kneeland	1951-91 1972-73 1966-73	USGS Brown, 1975 Brown, 1973, 1975
Peak discharge (flood) data	Mad R at Arcata	1910-13, 1950-92	USGS
Suspended sediment discharge measurements	Mad R at Arcata Mad R near Blue Lake Mad River near Kneeland	1957-73 1972-73 1970-73	USGS; Brown, 1973, 1975 USGS; Brown, 1975 USGS; Brown, 1973, 1975
Channel cross-sections	Blue Lake Bridge Collector 3 Collector 5 Pipeline Highway 299 Bridge Highway 101 Bridge	1982 1991 1960, 92 1960, 92 1960, 92 1941-91 1991 1960, 92 1929-89 1991	Humboldt Co. Bridge Plans Lehre/Lisle survey HBMWD HBMWD HBMWD CalTrans Lehre/Lisle survey HBMWD CalTrans Lehre/Lisle survey
Channel long profile	Mad R near Kneeland Mad R near Blue Lake Mad R at Hatchery Mad R in Guynup Bar reach Mad R in vicinity of Blue Lake Mad R in HBMWD reach Mad R between Hwy 299 and Hwy 101	1973? 1973? 1989 1990 1956 1992 1980	Brown, 1975 Brown, 1975 Lehre class Trinity Fisheries Consulting USCOE, 1956 HBMWD FEMA, 1986
Channel maps	Mad R from Hwy 101 bridge to Hatchery	1954-92	Trinity Restoration Associates

Bedload Transport Measurements

Brown (1975) reported nine measurements of bedload transport in the Mad River at Arcata (just upstream of the Highway 299 bridge), five in the Mad R near Blue Lake (just upstream from the hatchery), and five in the Mad River at Kneeland taken in water years 1972-73. These samples were collected during high flows using a Helley-Smith bedload sampler with a 0.25 ft (3 in) orifice and hence represent the bedload moving within 0.25 ft of the bed. Each reported measurement is the average of 4 to 7 samples taken across the channel. These measurements and the corresponding water discharges are given in Table 3.2.

Table 3.2 -- USGS Mad River bedload transport measurements

Gaging Site	Date	instantaneous water discharge Q cfs	instantaneous bedload discharge Q _b tons/day
Mad R at Arcata	28-Dec-71	1,390	291
	21-Jan-72	23,800	1,870
	24-Jan-72	10,000	451
	4-Mar-72	11,900	990
	25-Apr-72	1,210	34
	20-Feb-73	1,430	330
	1-Mar-73	3,850	753
	20-Mar-73	4,030	246
	12-Apr-73	980	6
Mad R near Blue Lake	20-Dec-72	2,410	2,680
	21-Feb-73	1,190	460
	28-Feb-73	3,250	988
	20-Mar-73	2,850	1,520
	10-Apr-73	986	994
Mad R near Kneeland	18-Jan-73	8,540	3,860
	26-Feb-73	4,240	1,140
	20-Mar-73	1,990	512
	3-Apr-73	1,620	85
	11-Apr-73	946	21

Bedload Transport Rating Curves

Brown plotted bedload transport rate against water discharge to create *bedload transport rating curves* for the three sites (Brown, 1975, figs. 9, 10, and 19). These are reproduced on a single graph in Fig. 3.1. From these curves and the 1971-72 water discharge records, he estimated the 1971-72 bedload discharge at Arcata as 60,000 tons (43,000 cu. yd. using a unit weight of 1.4 ton/cu. yd. for gravel) and 170,000 tons (121,000 cu. yd.) at Kneeland (Brown, 1975, p. 18 and p. 25). It must be emphasized that these estimates are quite crude, since his bedload transport curves are defined by very few points. These estimates of recruitment should be compared with the 200,000 -500,000 tons/yr (143,000 - 357,000 cu. yd./yr) that he estimates were extracted in the years 1961-70 (Brown, 1975, p. 55), which is 3 to 8 times the estimated transport at Arcata, and 1.2 to 3 times that at Kneeland. It should be noted that water year 1971-72 was a fairly wet year with substantial peak flows, so Brown's transport estimates were optimistic ones.

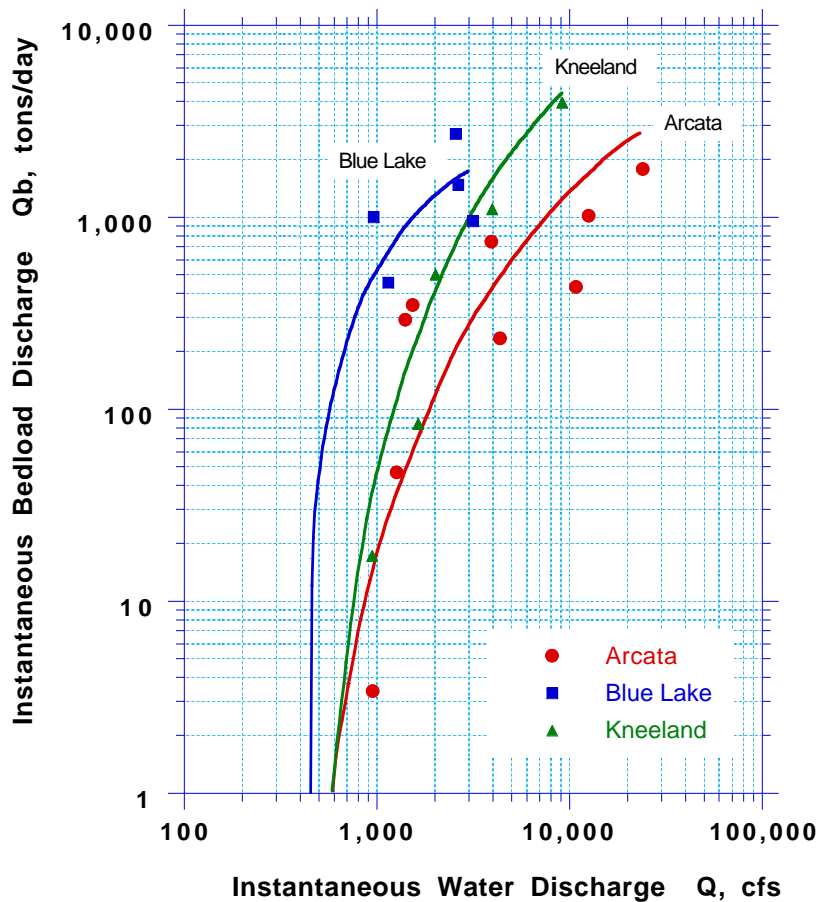


Fig. 3.1 --Bedload transport curves and data for the Mad River at Arcata, Blue Lake, and Kneeland, digitized from Brown (1975)

Bedload Transport Estimated Using Brown's (1975) Rating Curves

Lacking any better data, I estimated bedload discharge at Arcata by applying Brown's bedload transport curve for Arcata to USGS daily flow data for water years (WY) 1962 through 1992 at the gage. (WY 1962 was chosen as the starting date because Ruth Dam was closed across the upper Mad in July 1961.) The resulting daily bedload estimates were summed to yield the yearly totals of Table 3.3.

To estimate bedload transport at Kneeland, the eight years of daily flows (WY 1966-74) at the Kneeland gage were log-transformed and regressed on the corresponding log-transformed daily flows at Arcata. The resulting relations (Fig. 3.2) were used to synthesize daily flows at Kneeland for the periods 1962-65 and 1975-1992. Brown's bedload transport curve for Kneeland was applied to the combined data set and the daily estimates summed to produce the yearly totals in Table 3.3.

To estimate bedload transport at Blue Lake, the four years of daily flows (WY 1972-76) at the Blue Lake gage were log-transformed and regressed on the corresponding log-transformed daily flows at Arcata using a second-order polynomial. The resulting relation (Fig. 3.3) was used to synthesize daily flows at Blue Lake for the periods 1962-72 and 1977-1992. Brown's bedload transport curve for Blue Lake was applied to the combined data set and the daily estimates summed to get the yearly totals in Table 3.3.

Table 3.3 -- Bedload transport at Mad River sites estimated using Brown's (1975) rating curves

Note: To reduce round-off error when summing and averaging, quantities in Table 3.3 are given to more significant figures than justified; individual values should be rounded to the nearest thousand before citation or use. Tonnages were converted to cubic yards using a specific weight of 1.4 tons/cu. yd. (104 lb/cu. ft.)

WY	Estimated Bedload Discharge, tons			Estimated Bedload Discharge, cu. yd.		
	Kneeland	Blue Lake	Arcata	Kneeland	Blue Lake	Arcata
1962	62,491	147,975	27,916	44,636	105,696	19,940
1963	148,939	227,454	58,122	106,385	162,467	41,516
1964	86,093	176,981	35,717	61,495	126,415	25,512
1965	195,022	205,166	64,835	139,301	146,547	46,310
1966	96,212	171,757	36,919	68,723	122,683	26,371
1967	92,998	190,470	40,178	66,427	136,050	28,698
1968	60,999	127,988	24,648	43,571	91,420	17,605
1969	181,521	249,461	60,225	129,658	178,187	43,018
1970	167,677	159,958	48,164	119,769	114,256	34,403
1971	195,938	248,199	67,030	139,955	177,285	47,879
1972	143,905	205,599	53,386	102,789	146,856	38,133
1973	86,471	169,046	34,922	61,765	120,747	24,945
1974	270,120	320,303	94,196	192,943	228,788	67,283
1975	153,301	219,976	59,039	109,501	157,125	42,171
1976	54,782	134,193	25,210	39,130	95,852	18,007
1977	954	11,056	718	681	7,897	513
1978	148,169	251,363	60,278	105,835	179,545	43,056
1979	42,684	111,172	19,669	30,489	79,408	14,049
1980	114,905	216,626	47,922	82,075	154,733	34,230
1981	44,202	110,304	20,350	31,573	78,788	14,536
1982	220,267	309,011	85,141	157,334	220,722	60,815
1983	250,455	308,264	93,079	178,896	220,189	66,485
1984	165,629	266,781	66,121	118,306	190,558	47,230
1985	66,892	133,273	28,033	47,780	95,195	20,023
1986	150,023	176,749	53,544	107,160	126,249	38,245
1987	48,184	116,718	21,603	34,417	83,370	15,431
1988	44,020	85,295	18,290	31,443	60,925	13,064
1989	108,346	204,328	45,454	77,390	145,949	32,467
1990	47,363	124,418	22,428	33,830	88,870	16,020
1991	18,756	80,235	10,662	13,397	57,311	7,616
1992	12,097	53,889	6,806	8,641	38,492	4,861
Total	3,479,416	5,514,005	1,330,606	2,485,297	3,938,575	950,433
Mean yearly bedload discharge	112,239	177,871	42,923	80,171	127,051	30,659

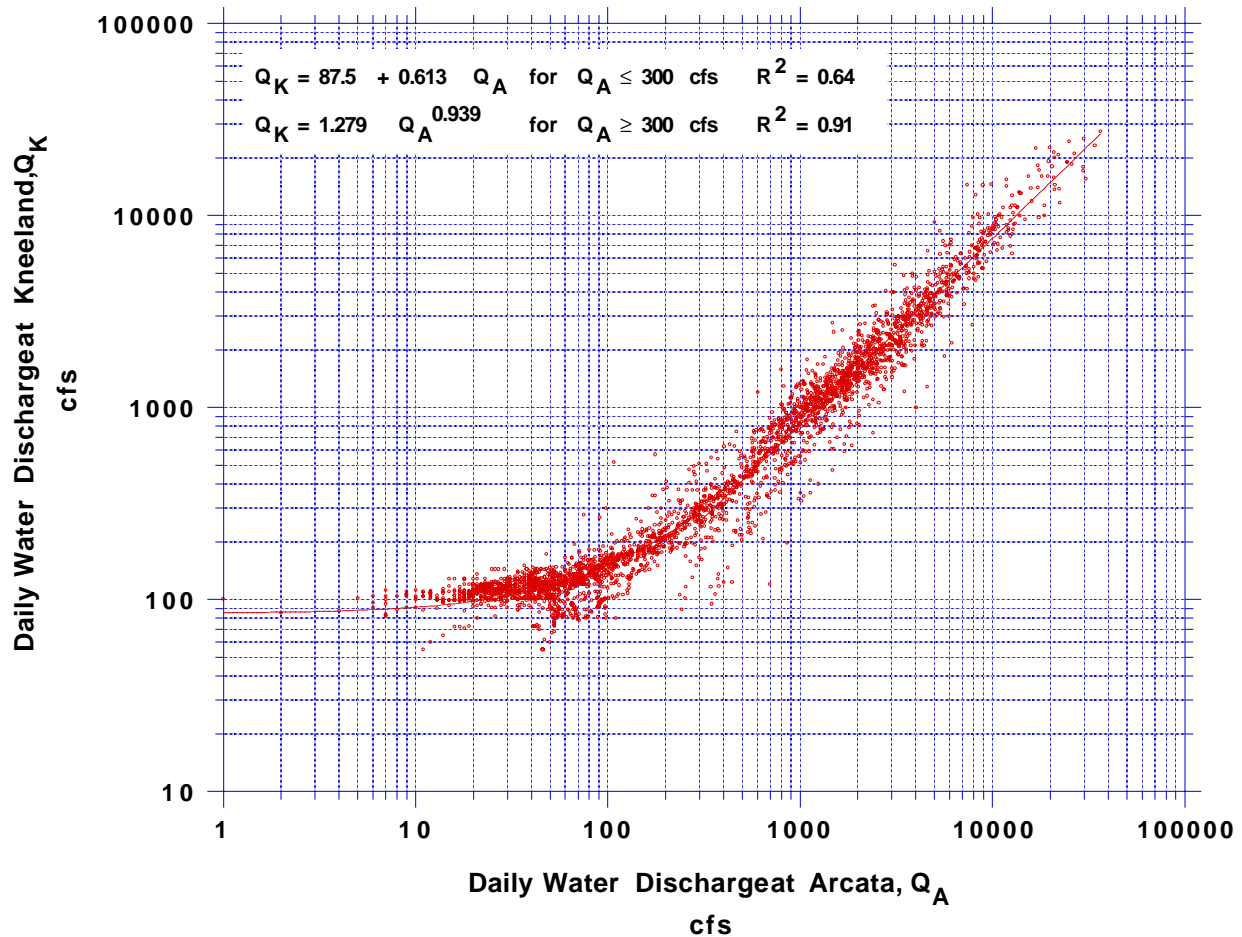


Fig. 3.2 -- Correlation of daily water discharge at Kneeland with daily water discharge at Arcata for WY 1966-1974.

Uncertainty of Rating Curve Estimates

The rating-curve estimates of bedload transport in Table 3.3 contain substantial but unquantifiable uncertainty. I believe, however, that they provide reasonable order-of-magnitude estimates of the bedload transport rate, especially on a long term average basis. The sources of error and their probable effects on the resulting estimates are discussed below.

Sampling error in bedload transport measurements: Bedload transport is highly variable in space, time, and particle size, even when water discharge is constant (e.g., Carson and Griffiths, 1987; Davies, 1987; Dietrich and Gallinatti, 1991; Hubbell, 1987). This makes sampling error a major source of uncertainty in determining bedload transport rates.

- a. *Spatial variation:* High rates of bedload transport tend to occur in relatively narrow longitudinal bands separated by wider areas of little or no gravel transport (Davies, 1987). For example, Thompson (1985) found on the Ohau R in New Zealand that even at high flows bed material was in motion over less than 10% of the channel width. The bands of significant transport are not necessarily fixed in position, but may migrate across the bed. Thus adequate spatial sampling across the channel is essential to define the mean transport rate. If the threads of high transport rate are missed, the true bedload discharge will be significantly underestimated; if, however, only such a thread happens to be sampled (as might happen with a single point measurement), the true bedload discharge will be greatly overestimated.

The USGS bedload measurements in Table 3.2 are averages of 4 to 7 samples taken at different points across the channel. While this number is not ideal (15 to 20 points would be better), it does suggest that spatial error is not likely to be excessive.

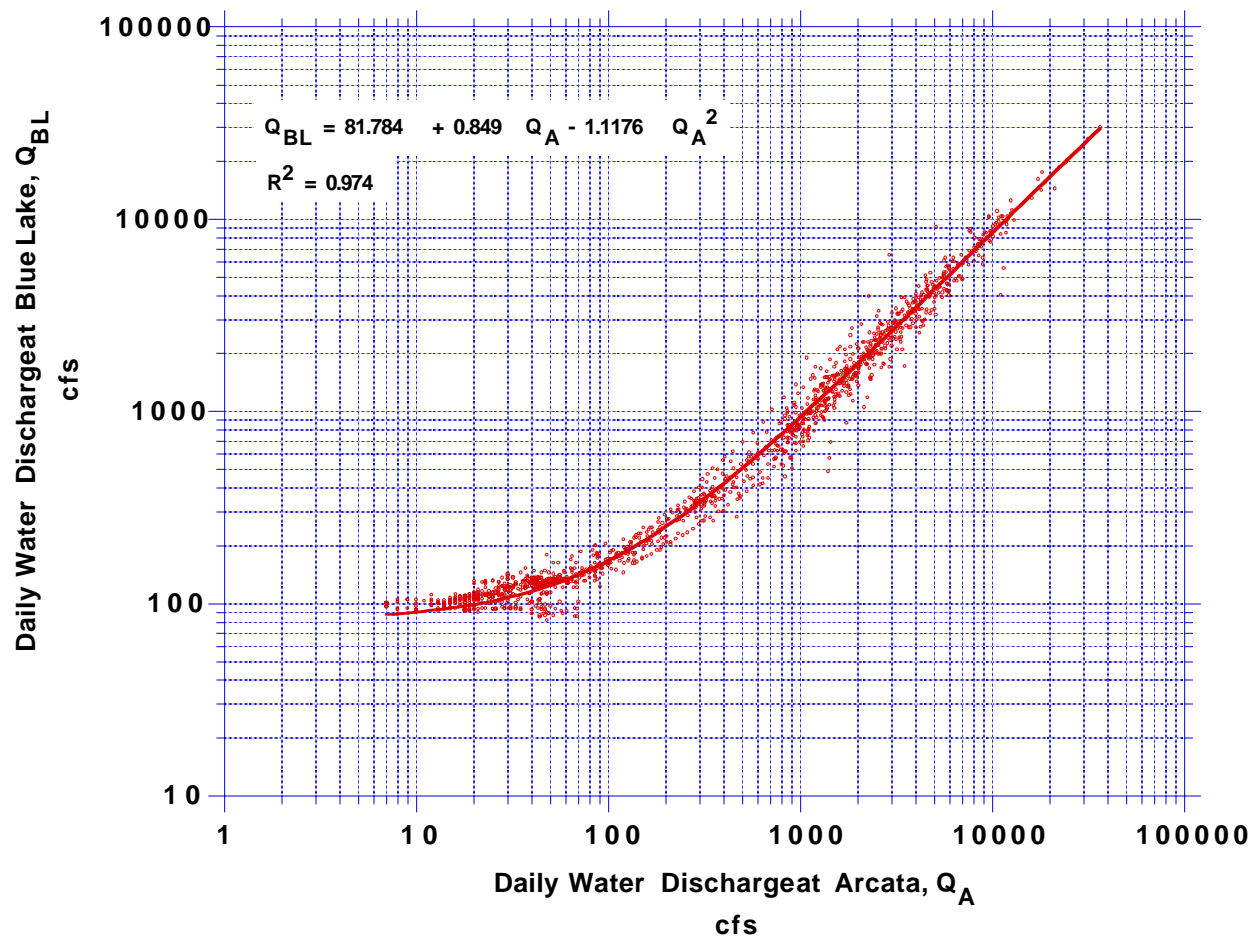


Fig. 3.3 -- Correlation of daily water discharge at Blue Lake with daily water discharge at Arcata for WY 1972-1976.

- b. *Temporal variation:* Bedload movement is also typically highly unsteady in time, and transport rates may easily vary by a factor of 2 or more over periods of several minutes to several hours, even when flow is constant. Time variation is especially pronounced when bedload is primarily sand. A single bedload measurement may easily grossly over- or underestimate the true mean transit rate at a point. The USGS data is clearly insufficient in this regard, but there is no way to tell whether the measurements err on the high or low side. From sample to sample these errors may partially cancel, but a particularly low or high value could strongly affect the position of the bedload transport curve.
- c. *Particle size:* The particle-size of bed material in transport is governed by both the availability of transportable sizes and the hydraulic characteristics of the flow. As the bed and banks of gravel-bed rivers are commonly quite heterogeneous (e.g., Lisle and Madej, 1992), the particle sizes available for transport may vary widely across the channel. In addition, the particle sizes in transport will vary with time as new bed material is exposed through local disruption of the coarser surface layer (pavement). Since transport rate is strongly related to particle size, these size fluctuations will cause concomitant fluctuations in bedload discharge.

A second type of size sampling error is caused by the dimensions of the Helley-Smith sampler itself. The orifice is 3 in (76 mm) wide. Any particles larger than about 20% of this value (i.e., larger than 15 mm) will tend to be undersampled, and particles larger than 76 mm won't be sampled at all. Thus if large particles are a dominant component of the bed-material load, the load will be underestimated. Judging from the 90th percentile size of the bedload samples, size-related undersampling may be a significant problem at the Kneeland site, a moderate problem at Arcata, and a mild problem at Blue Lake.

Error in fitting the bedload rating curves: The high degree of variability in the bedload discharge measurements, together with the very small number of samples makes fitting the bedload curves problematic. (A large scatter -- often over one to two orders of magnitude -- is typical of points defining bedload transport curves.) The general convex-upward shape of bedload rating curves is well known from measurements on other rivers, and provides some guide to fitting a curve to the observations. Brown (1975) evidently fit his curves (Fig. 3.1) by eye, so there is no way to assess their prediction error. The Arcata and Kneeland curves really look quite good, but the Blue Lake curve is very uncertain -- the points are too clustered to be able to define the curve well. Because the upper end is so ill-defined, it may easily overestimate bedload transport. I have not attempted to re-fit Brown's data; as the field investigator he would have known best how to interpret the measurements.

Error in estimating daily water discharges at Blue Lake and Kneeland: Regressions on mean daily flow at Arcata (Figs. 3.2 and 3.3) were used to synthesize water discharges at Blue Lake and Kneeland for the years they were not gaged. The points cluster tightly around the regression lines, and for the larger flows, where bedload transport becomes significant (above 800 cfs or so), the maximum scatter is less than $\pm 50\%$. This is really quite good, and the errors will tend to cancel out.

Uncertainty in the temporal applicability of the rating curves: The bedload transport data were collected in WY 1972-73. I have had to assume that rating curves constructed from these data are valid for the entire period 1962-1992, i.e. that over that time span the relationship between water discharge and bedload discharge has remained the same at all three sites. This is a dubious proposition, for several reasons.

First, the bedload data were collected only three years after the removal of Sweasey Dam had released a large amount of coarse sediment into the Mad. This abundant supply of bedload would tend to shift the rating curve upward (higher bedload discharge for a given water discharge), leading to overestimates for years 1) prior to the removal of the dam and 2) following the passage of the slug of sediment downstream. This would not affect the Kneeland gage (upstream from Sweasey Dam) but would certainly affect the Blue Lake and possibly the Arcata gage.

Second, the 1964 flood reorganized the channel and certainly changed the availability of sediment in the Mad. The particular effects of this flood on subsequent bedload transport is unknown, but, based on observations on other streams, it is likely that it also shifted the rating curves upward. How long its effects on bedload transport might have persisted is not known.

Third, the bedload transport measurements were made in or after reasonably wet years, when substantial amounts of bedload would likely be available for transport. This again would tend to move the rating curves upward. It is likely that they overpredict for drier periods.

Fourth, the effects of gravel mining on the applicability of the curves is not known. Large extraction volumes would tend to deplete the amount of gravel available for transport at downstream sites. Mining is not likely to have appreciably affected the Kneeland or Blue Lake curves, but might well cause post-1973 transport rates at Arcata to be less than the curve would indicate.

Use of daily mean discharges with an instantaneous discharge rating curve: The use of daily mean discharges (all we have) generally underestimates the sediment load. Bedload transport goes up as a power function of discharge, not linearly, so averaging the higher and lower flows of each day will yield estimates smaller than those we would get if we could use hourly data. This error is likely to be on the order of 5 - 15%.

Estimated bed-material recruitment from bedload rating curves

Long term mean annual bed-material recruitment on the Mad River estimated using Brown's bedload rating curves ranged from a low of 43,000 tons/yr (31,000 yd³/yr) at Arcata to a high of 178,000 tons/yr (127,000 yd³/yr) at Blue Lake (Table 3.3). Despite the many possible sources of error in these figures (see preceding section), I believe that these estimates are generally in the right range. The values estimated for specific years may well be off the mark, but *over the long term* it seems likely that errors of overestimation will be at least partly canceled by errors of underestimation. These figures suggest that long-term *average* recruitment to the upper end of the extraction reach (i.e., vicinity of Guynup Bar) is on the order of 150,000 to 200,000 tons (110,000 - 140,000 yd³) annually. The lower rates of bedload transport observed at the Arcata gage may reflect: 1) the effects of upstream gravel extraction reducing the flow of gravel downstream, 2) the continuing breakdown of gravel particles to sand during

downstream transport, or 3) sampling difficulties at the Arcata gage which resulted in catches which underestimated the true transport rate.

Bedload Transport Equations

Over the past century, engineers have proposed at least fifty different equations for estimating rates of bedload transport. The equations attempt to relate the bedload transport rate to the particle size of the bedload and the hydraulic conditions (e.g., slope, depth, width, bed shear stress, velocity, discharge) in the stream. Most of the equations consist of some theoretical construct with constants calibrated from experiments in flumes or, more rarely, natural rivers; a few are strictly empirical. All work best when they are applied to conditions (e.g., particle size, slope, depth, width) similar to those under which they were derived (*see* Carson and Griffiths, 1987; Gomez and Church, 1989; Reid and Dunne, 1992; Vanoni, 1975); none works well under all conditions.

The equations I chose to use on the Mad River were either ones that have been commonly applied to gravel-bed streams in the past (Einstein-Brown, Meyer-Peter, and Meyer-Peter-Müller equations), or which were recommended in recent papers (Gomez and Church, 1989; Reid and Dunne, 1992) as especially promising (Ackers-White and Bagnold 1980 equations). All have been calibrated either by using gravel in flumes, or on natural gravel rivers. Discussions of the strengths and weaknesses of the equations are given by Carson and Griffiths (1987), Gomez and Church (1989), Reid and Dunne (1992), Vanoni (1975), and White et. al. (1973b). Formulas and calculational details of the equations are given in Bagnold (1980), Vanoni (1975), and White et. al. (1973a). All calculations were carried out using Microsoft Excel spreadsheets programmed by me.

Computation of long-term bedload discharge: The complexity and uncertainty of bedload equations made it impractical to compute bedload discharge on a day-by-day or year-by-year basis. Instead, I used each equation to estimate the 30-year mean bedload discharge by: 1) computing the 30-year cumulative frequency distribution of flows at each gage (flow-duration curve); 2) dividing the logarithms of the discharges into 50 equal size classes; 3) computing the bedload discharge corresponding to the median discharge of each size class; 4) multiplying this bedload estimate by the fraction of time in the class; and finally 5) summing the products to get the mean transport rate. The same strategy is commonly used to estimate suspended-sediment discharge.

Data Required for the Equations

The various equations require as input estimates of water discharge (Q), mean depth (d), mean velocity (v), channel width (w), longitudinal water-surface slope (S), and one or more parameters characterizing the diameter (D) of the sediment particles.

Hydraulic parameters: The *hydraulic geometry* of a stream at a gaging station consists of straight-line plots, on log-log paper, of the variation with discharge of width, mean depth, and mean velocity. These lines yield equations of the form $w = aQ^b$, $d = cQ^f$, and $v = kQ^m$, where a , c , k , b , f , and m are constants. (The necessary measurements are made routinely during stream gaging, and are summarized by the USGS on form 9-207.) Given the hydraulic geometry at a site, it is easy to estimate the width, depth, and velocity corresponding to any discharge.

Equations defining the Blue Lake and Kneeland hydraulic geometry were scaled from plots in Brown (1975, p. 44-45.) The hydraulic geometry at Arcata (Fig. 3.4) was constructed from 9-207's supplied by the USGS. Channel slope at Kneeland and Blue Lake are given by Brown (1975, p. 44-45); slope at the Arcata gage was estimated from 1992 HBMWD surveys and Mad River flood profiles (FEMA, 1986.)

Particle-size parameters: Particle-size parameters used in the equations were D_{mean} (average diameter) D_{50} (median diameter), and D_{90} (diameter for which 90% of the particles are smaller). These were calculated from published size analyses of the USGS bedload and bed material samples. The median value of each parameter was used in the computations. Particle-size parameters computed for this study are summarized in Table 3.4.

Table 3.5 summarizes the hydraulic geometry relations, slope, and particle size parameters used in the bedload computations at each site.

The 1962-1992 mean annual bedload recruitment estimates computed with each equation are compared with each other and with the rating curve and suspended-load percentage estimates in Table 3.6. The Einstein-Brown relation was not used because it performed so badly in calibration tests (see below).

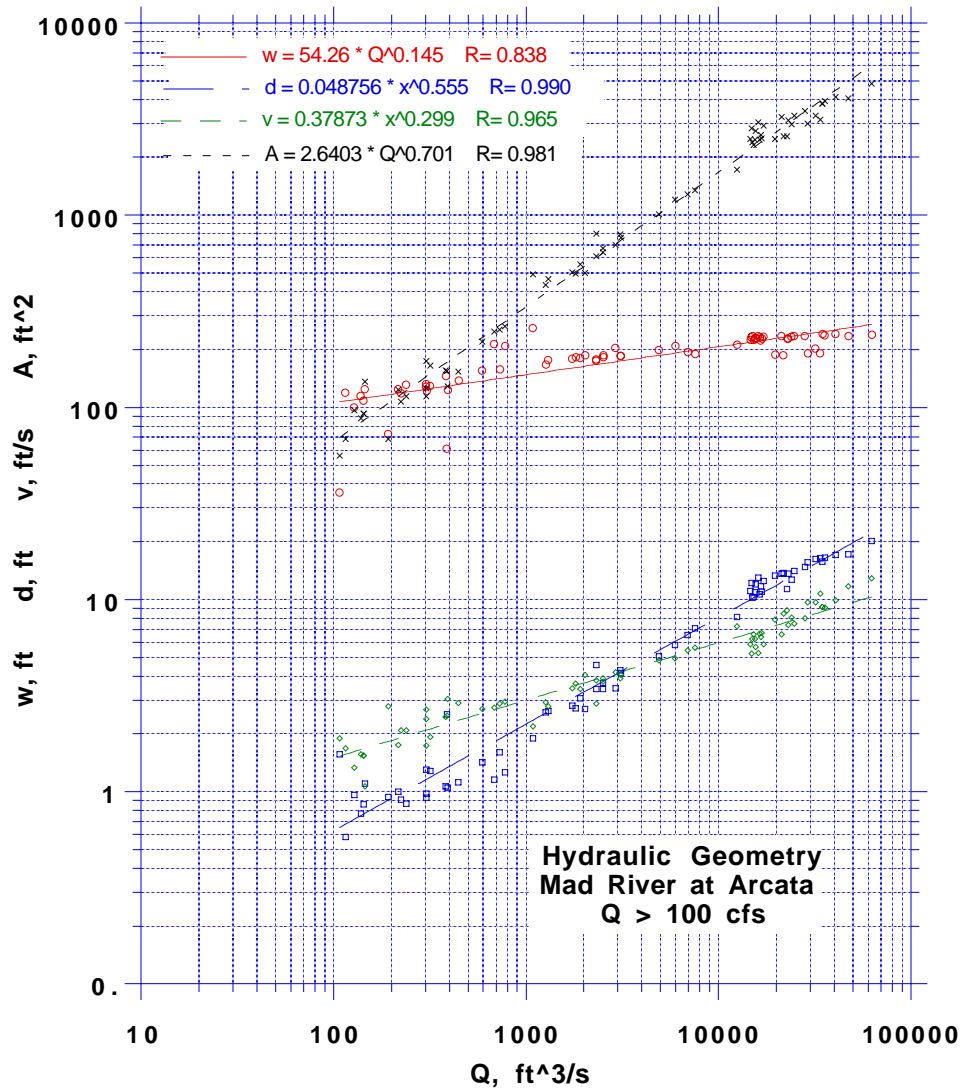


Fig 3.4 -- Hydraulic geometry at Arcata for discharges greater than 100 cfs

Table 3.4a -- Size parameters for USGS bedload samples at Kneeland gage

Date	Type	Q cfs	D90 mm	D84 mm	D65 mm	D50 mm	D35 mm	D16 mm	D10 mm	Dmean mm
18-Jan-73	bedload	8540	32.0	23.43	12.12	8.00	4.36	1.19	0.70	12.31
26-Feb-73	bedload	4240	44.00	35.00	13.83	6.50	2.17	0.67	0.48	14.09
20-Mar-73	bedload	1990	22.77	14.85	14.85	5.83	3.65	1.19	0.70	9.53
3-Apr-73	bedload	1620	35.0	18.16	3.55	1.76	1.19	0.72	0.58	8.81
11-Apr-73	bedload	946	7.32	4.76	1.89	1.27	0.89	0.57	0.47	2.71
	median		32.00	18.16	12.12	5.83	2.17	0.72	0.58	9.53
	mean		28.22	19.24	9.25	4.67	2.45	0.87	0.59	9.49
	std dev		13.93	11.14	6.07	2.99	1.52	0.30	0.11	4.35
	max		44.00	35.00	14.85	8.00	4.36	1.19	0.70	14.09
	min		7.32	4.76	1.89	1.27	0.89	0.57	0.47	2.71

Table 3.4b -- Size parameters for USGS bedload and bed material samples at Blue Lake gage

Date	Type	Q cfs	D90 mm	D84 mm	D65 mm	D50 mm	D35 mm	D16 mm	D10 mm	Dmean mm
20-Dec-72	bedload	2410	9.4	6.70	2.79	1.59	0.98	0.58	0.47	3.22
21-Feb-73	bedload	1190	10.41	8.00	3.86	2.35	1.41	0.66	0.48	4.29
28-Feb-73	bedload	3250	12.10	9.01	3.78	1.68	0.85	0.48	0.40	4.66
20-Mar-73	bedload	2850	9.7	7.44	4.47	3.19	2.26	1.16	0.78	4.21
10-Apr-73	bedload	986	11.33	8.62	4.87	3.33	2.24	1.29	1.00	5.34
22-Oct-89	bed surface*	140	25.38	22.85	16.27	12.87	8.59			12.93
22-Oct-89	bed surface*	140	40.51	31.15	18.84	9.51	5.78			16.18
	median		11.33	8.62	4.47	3.19	2.24	0.66	0.48	4.66
	mean		16.98	13.40	7.84	4.93	3.16	0.83	0.63	7.26
	std dev		11.79	9.63	6.71	4.43	2.92	0.37	0.26	5.11
	max		40.51	31.15	18.84	12.87	8.59	1.29	1.00	16.18
	min		9.40	6.70	2.79	1.59	0.85	0.48	0.40	3.22

* not USGS. Pebble count opposite hatchery by HSU Geology 550 class.

Table 3.4c -- Size parameters for USGS bedload and bed material samples at Arcata gage

Date	Type	Q cfs	D90 mm	D84 mm	D65 mm	D50 mm	D35 mm	D16 mm	D10 mm	Dmean mm
28-Dec-71	bedload	1390	5.56	4.17	2.23	1.53	1.05	0.55	0.43	2.56
21-Jan-72	bedload	23800	24.72	16.88	6.29	3.01	1.61	0.54	0.39	8.50
24-Jan-72	bedload	10000	29.29	19.05	8.56	5.09	2.72	0.47	0.32	10.08
4-Mar-72	bedload	11900	37.00	26.14	9.29	4.00	1.60	0.54	0.38	11.36
25-Apr-72	bedload	1210	1.78	1.50	1.05	0.71	0.48	0.36	0.31	1.10
20-Feb-73	bedload	1430	2.38	1.83	0.95	0.95	0.77	0.55	0.47	1.51
1-Mar-73	bedload	3850	9.23	6.91	1.33	1.33	0.85	0.47	0.38	3.30
20-Mar-73	bedload	4030	4.68	2.75	0.49	0.49	0.41	0.30	0.26	1.87
12-Apr-73	bedload	980	0.76	0.56	0.36	0.36	0.31	0.25	0.19	0.63
20-Nov-72	bed surface	664	18.00	13.31	6.50	3.07	1.39	0.59	0.45	6.36
20-Nov-72	bed surface	664	15.16	11.66	6.11	3.49	1.70	0.63	0.46	5.99
20-Nov-72	bed surface	664	8.50	6.23	2.86	1.38	0.75	0.41	0.34	3.03
20-Nov-72	bed surface	664	23.00	19.00	10.73	7.39	4.00	0.76	0.46	9.11
20-Nov-72	bed surface	664	21.00	16.00	11.16	8.88	5.60	1.72	1.00	9.55
20-Nov-72	bed surface	664	27.00	25.00	18.00	13.94	11.03	6.89	4.00	14.53
20-Nov-72	bed surface	664	15.00	13.00	10.50	8.50	5.18	1.61	1.26	7.61
	median		15.08	12.33	6.20	3.04	1.50	0.55	0.41	6.18
	mean		15.19	11.50	6.03	4.01	2.47	1.04	0.69	6.07
	std dev		11.08	8.39	5.09	3.86	2.82	1.61	0.92	4.22
	max		37.00	26.14	18.00	13.94	11.03	6.89	4.00	14.53
	min		0.76	0.56	0.36	0.36	0.31	0.25	0.19	0.63

Table 3.5 -- Input data for bedload equations

		Arcata	Blue Lake	Kneeland
width	ft	$w = 54.26 Q^{0.145}$	$w = 34.2 Q^{0.25}$ $Q \leq 1200$ cfs	$w = 8.00 Q^{0.40}$ $Q \leq 1000$ cfs
			$w = 2.88 Q^{0.60}$ $Q > 1200$ cfs	$w = 56.8 Q^{0.10}$ $Q > 1000$ cfs
depth	ft	$d = 0.049 Q^{0.555}$	$d = 0.074 Q^{0.44}$ $Q \leq 1200$ cfs	$d = 0.460 Q^{0.20}$ $Q \leq 1000$ cfs
			$d = 0.406 Q^{0.20}$ $Q > 1200$ cfs	$d = 0.021 Q^{0.65}$ $Q > 1000$ cfs
velocity	ft/s	$v = 0.379 Q^{0.299}$	$v = 0.395 Q^{0.31}$ $Q \leq 1200$ cfs	$v = 0.270 Q^{0.40}$ $Q \leq 1000$ cfs
			$v = 0.855 Q^{0.20}$ $Q > 1200$ cfs	$v = 0.830 Q^{0.25}$ $Q > 1000$ cfs
slope		0.0016	0.0028	0.0053
D ₉₀	mm	15	11	32
D ₅₀	mm	3	3	6
D _{mean}	mm	6	5	9.5

Table 3.6 -- Comparison of long-term mean bedload transport estimates for the Mad River

estimation procedure	mean bedload transport 1962-1992, tons/yr			mean bedload transport 1962-1992, yd ³ /yr		
	Arcata	Blue Lake	Kneeland	Arcata	Blue Lake	Kneeland
Brown 1975 rating curve	42,900	178,000	112,000	30,600	127,000	80,200
Ackers-White eqn	106,000	299,000	251,000	75,600	213,000	179,000
Bagnold 1980 eqn	151,000	349,000	649,000	108,000	249,000	463,000
Meyer-Peter eqn	220,000	452,000	1,269,000	157,000	323,000	907,000
Meyer-Peter & Müller eqn	180,000	587,000	876,000	128,000	419,000	626,000
As 5% of suspended load	83,600	--	45,500	59,700	--	32,500
As 10 % of suspended load	167,000	--	91,000	119,000	--	65,000

Bedload Equation Performance

The performance of each bedload equation was tested by comparing its predictions -- computed using the particle size distribution of each bedload sample and the corresponding water discharge -- to the observed transport rates. In Fig. 3.5 I have plotted the observed and computed bedload transport rates against water discharge. The bedload equations almost without exception predict transport rates 2 to 10 times -- and sometimes as much as 1000 times-- greater than the observed rates. Fig. 3.5 shows that the Ackers-White and Bagnold 1980 equations generally performed the best, while the Einstein-Brown equation consistently gave results 100 to 1000 times larger than the observed values. On this basis I discarded further use of the Einstein-Brown relation.

This overprediction of transport rates is typical of bedload equations (Gomez and Church, 1989), and is caused by several factors:

- 1) the equations assume a one-dimensional steady-state equilibrium between transport processes and flow that applies uniformly across the channel. This is unrealistic as transport rates in natural channels are always observed to fluctuate widely in space and time (cf. discussion on p. 7-8).
- 2) the equations assume that there are no limitations on supply of particles of the size that can be moved by the flow. In reality, natural bed armoring by coarser particles may reduce the supply to well below the stream's transport capacity.

- 3) the use of hydraulic parameters averaged across the whole channel (e.g., mean depth, mean slope, mean velocity, mean shear stress) significantly overestimates transport. The shear stress (tractive stress) actually experienced by the bed particles is usually significantly less than the channelwide mean value, which includes flow resistance caused by bedforms, channel configuration, and bank roughness, as well as grain stress (Carson and Griffiths, 1987; Gomez and Church, 1989). Partitioning the channel into subsections and use of local depth and slope measurements reduces the overestimation (Carson and Griffiths, 1987; Thompson, 1985), but such data is not generally available without prior planning for its collection.

The long term mean estimates of annual recruitment (Table 3.5) suffer in addition from the following errors:

- 4) the hydraulic geometry of the Mad River is not known for flows exceeding 20,000 cfs at Kneeland and 4,000 cfs at Blue Lake. To cover higher discharges I had no choice other than to extend Brown's relations as straight lines. This is almost certainly in error, especially at the Blue Lake site, where the hydraulic geometry predicts an unreasonably wide channel at high flows. Without channel surveys at these sites it is impossible to assess the extent and seriousness of the errors.
- 5) the hydraulic geometry and longitudinal slope at the gaging sites must be assumed to have remained constant with time. The extent to which this is likely at Blue Lake and Kneeland is unknown. The hydraulic geometry at the Arcata gage appears to have changed little with time for flows > 100 cfs (Fig. 3.4). Since the Mad River has lowered its bed up to 8 feet in the past 30 years, it is likely that the longitudinal slope has changed with time. We have no information which allows us to assess the extent to which this has occurred.
- 6) the equations are generally quite sensitive to the grain size used in the computations. Doubling the grain size can easily halve the predicted sediment load or worse. The dominant particle size in bedload transport assuredly varies with time, spatial position in the channel, and discharge. This variation is unknown and thus we have no basis for using anything but a constant grain size for all calculations at a site. This is a significant source of error.

In addition, there is the problem of *what* measured grain size should be used in the calculations. Research over the last decade suggests that the particles in bedload transport are generally closer in size to those particles *in* the bed (i.e., beneath the surface layer) than they are to those on the bed surface. Lacking any better procedure, it seemed reasonable to use the median value of the bedload-sample size parameters (D_{50} , D_{90} , D_{mean}) at each site. Again, this may be a significant source of error.

Estimated mean annual bed-material recruitment from bedload equations

Long term mean annual bed-material recruitment on the Mad River estimated using four bedload equations ranged from a low of 106,000 tons/yr (76,000 yd³/yr) with the Ackers-White equation at Arcata to a high of 1,269,000 tons/yr (906,000 yd³/yr) with the Meyer-Peter equation at Kneeland (Table 3.6). Consideration of the assumptions underlying the bedload equations and their general lack of agreement, as well as comparison of predicted with observed transport rates (Fig. 3.4) suggests that the equations in general significantly overestimate the true mean recruitment rate. The most consistent estimates are those at the Arcata gage, which suggest average annual recruitment of 100,000 to 200,000 tons (70,000 - 140,000 yd³). This seems the right order of magnitude. The estimates at the Blue Lake and Kneeland gages scatter very widely, with the highest and lowest values differing by a factor of 6. I do not trust these values and believe that at Kneeland and Blue Lake the equations greatly overestimate recruitment. The Ackers-White estimates of 250,000-300,000 tons/yr (180,000 - 215,000 yd³/yr) at these sites probably provide an upper bound on average annual resupply.

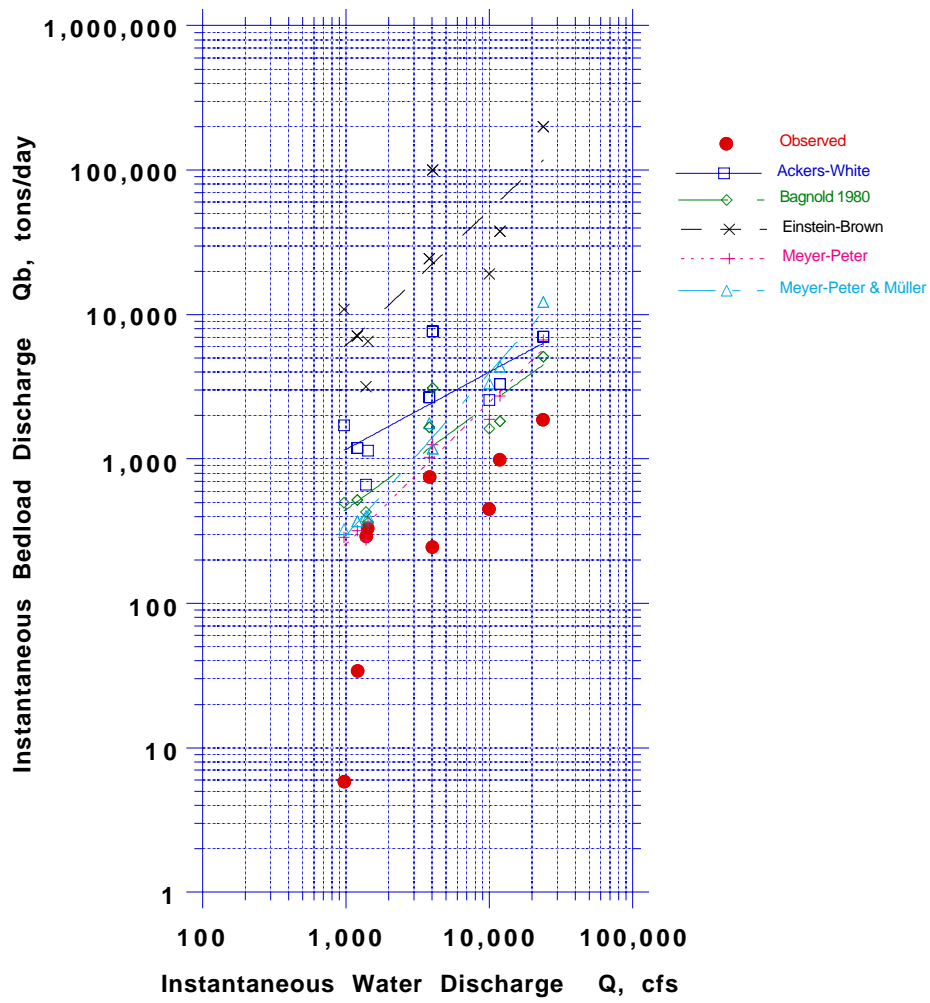


Fig. 3.5a -- Comparison of observed and predicted bedload transport rates at Arcata gage

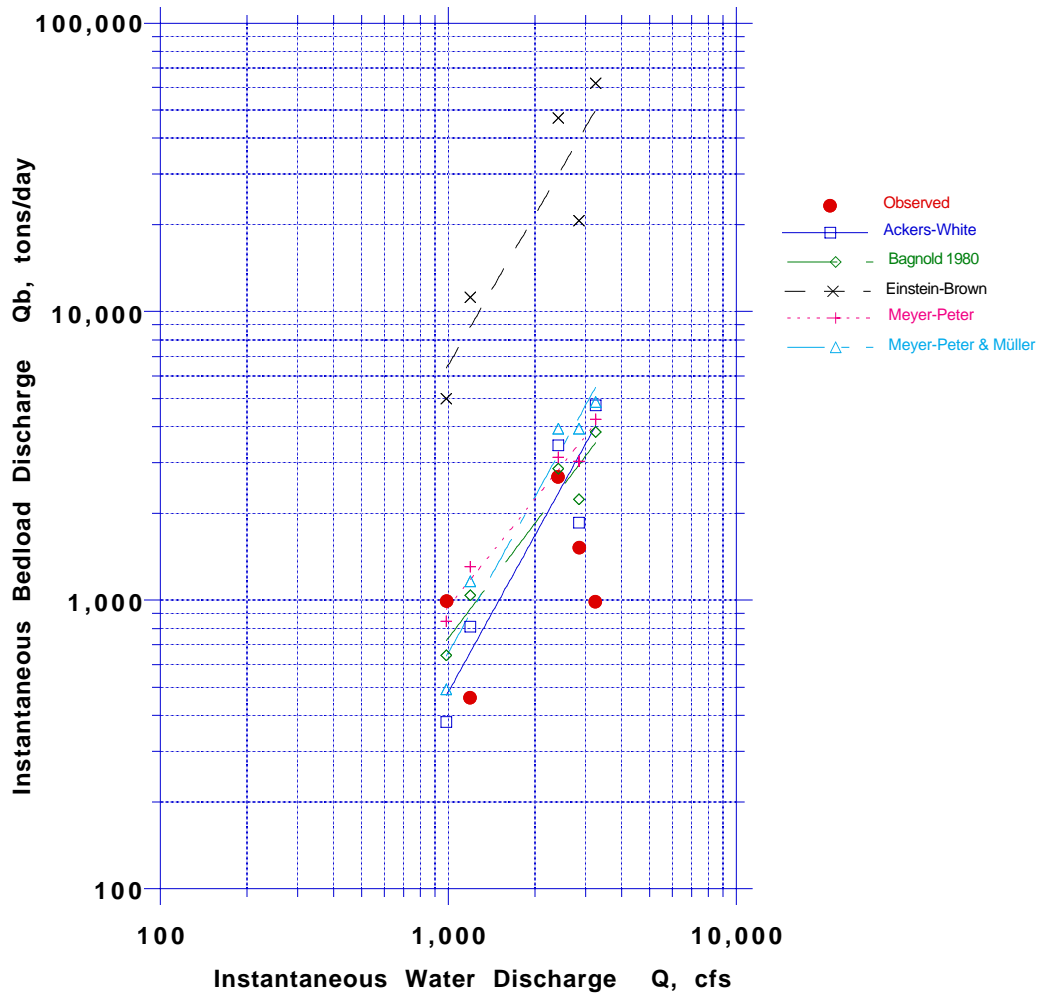


Fig. 3.5b -- Comparison of observed and predicted bedload transport rates at Blue Lake gage

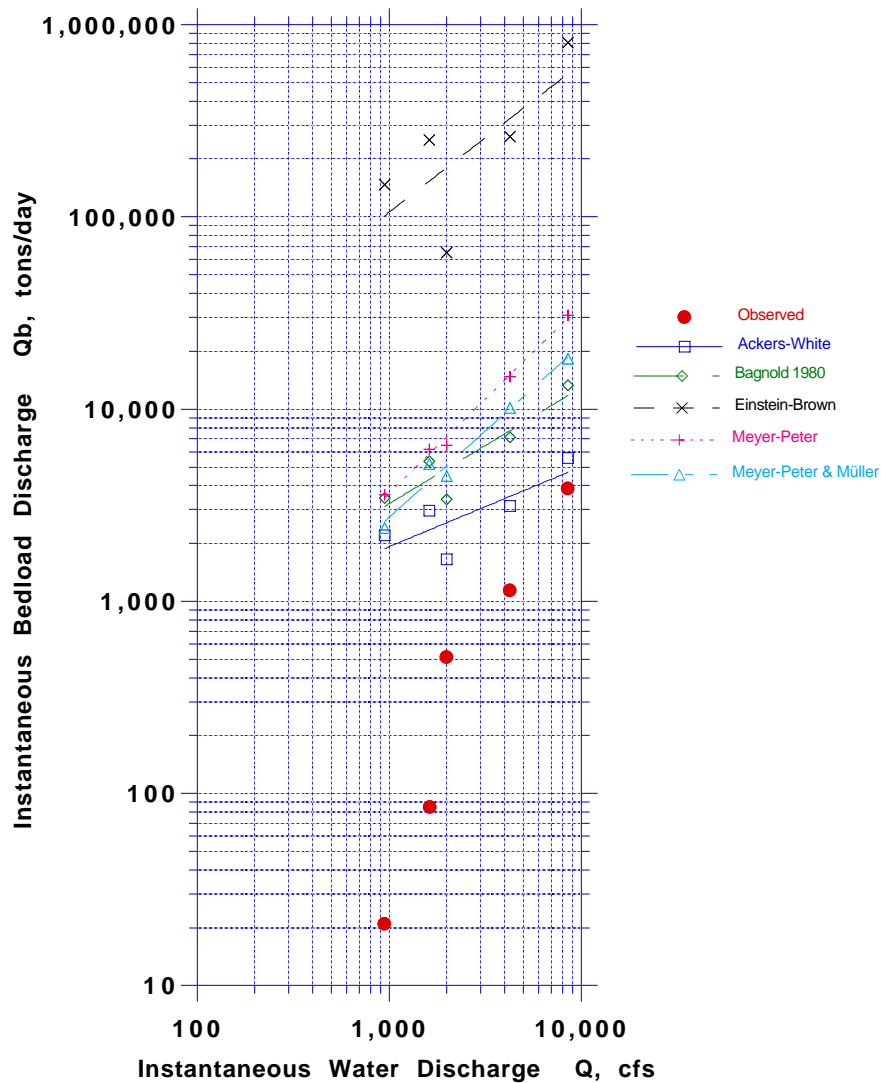


Fig. 3.5c -- Comparison of observed and predicted bedload transport rates at Kneeland gage

Estimating Bedload Transport as a Percentage of the Suspended Load

Finally, a crude but usable method for estimating mean annual bedload recruitment is to compute it as a fixed percentage of the average annual suspended-sediment load based on observations on rivers where both suspended load and bedload have been measured (e.g., Collins and Dunne, 1990; Reid and Dunne, 1992). According to data presented in Reid and Dunne (1992, Table 12), the bedload discharge of gravel-bed rivers is characteristically equal to about 4-5% of their suspended load discharge; 10% seems a typical upper limit.

To estimate the suspended-load discharge at Arcata and Kneeland, I applied Brown's suspended-sediment discharge curve (Brown, 1975, Fig. 14) to daily water discharges for the period 1962-1992 at Arcata (observed) and Kneeland (observed plus synthesized). The resulting daily suspended-load estimates were summed to give the yearly estimates in Table 3.7. Suspended-load data was not available for the Blue Lake site. It should be noted that Brown's curve is quite well-defined, being based on a large number of samples taken over several years.

Computing mean annual bedload discharge as 5% of the mean annual suspended load yields estimates of 46,000 -84,000 tons/yr (33,000 -60,000 yd³/yr), while estimating it at 10% of the suspended load (a likely upper limit) gives mean annual recruitment of 91,000 -167,000 tons/yr (65,000 -119,000 yd³/yr). Both estimates have been entered in Table 3.6 for comparison with the other methods.

Table 3.7 -- Suspended-load transport at Mad River sites estimated using Brown's (1975) rating curve

Note: To reduce round-off error when summing and averaging, quantities in Table 3.7 are given to more significant figures than justified; individual values should be rounded to the nearest thousand before citation or use.

WY	Estimated Suspended-Load Discharge, tons	
	Kneeland	Arcata
1962	289,412	521,008
1963	998,951	1,957,140
1964	707,672	1,455,183
1965	2,824,846	6,462,996
1966	790,124	1,674,069
1967	587,928	1,039,300
1968	416,732	551,596
1969	2,080,017	2,214,490
1970	2,159,346	2,965,339
1971	1,964,178	2,776,911
1972	1,343,810	3,223,401
1973	478,360	717,933
1974	2,410,880	4,222,285
1975	1,237,707	2,547,387
1976	284,535	518,908
1977	8,547	11,602
1978	844,606	1,619,995
1979	185,557	327,200
1980	672,083	1,291,124
1981	198,152	352,220
1982	1,545,735	3,100,750
1983	1,815,575	3,651,493
1984	1,007,427	1,947,504
1985	373,910	706,151
1986	1,627,517	3,508,748
1987	215,954	384,398
1988	242,316	453,663
1989	568,594	1,068,726
1990	208,484	370,459
1991	79,526	130,521
1992	53,453	86,859
mean yearly suspended-load discharge	910,385	1,672,883

Summary of Bedload Transport Estimates

Average annual bedload recruitment to the Mad River below the hatchery was estimated with three different techniques: bedload rating curves, bedload transport equations, and ratio to suspended load. The two methods based on actual field measurements agree reasonably well and suggest that true mean annual recruitment lies somewhere in the range of 50,000 - 200,000 tons/yr (35,000 - 140,000 yd³/yr). The bedload equations give inconsistent results which almost certainly overpredict the load at the upstream sites. The equations give more consistent results at Arcata, again suggesting that average annual recruitment lies in the range of 100,000 - 200,000 tons/yr (70,000 - 140,000 yd³/yr). In my opinion, a reasonable estimate of mean annual recruitment for planning purposes is 150,000 yd³/yr, with 200,000 yd³/yr certainly a ceiling.

ANALYSIS OF BED DEGRADATION

Amount of bed lowering since 1960

As stated in the introduction, the bed of the Mad River between the hatchery and the Highway 101 has undergone significant and consistent degradation (lowering) over the past 32 years. Evidence from CalTrans bridge surveys suggests that bed lowering has been going on since at least 1929. The data presently available to us are insufficient to allow us to address the possible causes of this earlier lowering; our analysis is restricted to bed degradation since 1960 between the hatchery and the Highway 101 bridge, which is reasonably well documented.

The quantitative data used in this study are summarized in Table 3.8; for further information the reader is referred to Table 3.1 and the Introduction (p. 1-2). The bulk of our measurements come from repeated cross-sections at bridge sites, with additional data available from cross-sections and observations in the HBMWD reach, which extends from the Railroad Bridge down to Highway 299. These cross-sections are included as an appendix (Figs. 3.A1 – 3.A4).

The mean yearly lowering rates for the period 1960 - 1992 are remarkably consistent along the river from the Blue Lake (Hatchery Road) Bridge down to Highway 101, ranging from 0.11 to 0.27 ft/yr and averaging about 0.15 ft/yr. This means that the entire width of the bed has been lowered about 5 feet since 1960.

Bridge sites are notorious for scour because bridges typically narrow the channel and hence speed up the river. This has undoubtedly occurred to some extent in the maximum scour at Hwy. 299. The fact, however, that the mean lowering rates at the bridge sites are consistent with each other, with the rates in the HBMWD reach, and with the observed downcutting at tributary mouths strongly suggests that the bridge cross-sections are reasonably representative of overall bed lowering.

Table 3.8 -- Summary of bed degradation measurements used in study

Site	Period	Δ Time	Maximum Lowering	Mean Lowering	Scour Width	Δ Area	Mean Lowering Rate	Source
		yr	ft	ft	ft	ft ²	ft/yr	
Blue Lake Bridge	1982-91	9	4.5	1.6	181	290	0.18	Lehre/County
Collector 3	1960-92	32	7.2	3.5	638	2231	0.11	HBMWD
Collector 5 (incomplete xs)	1960-92	32	9.6	4.2	492	2089	0.13	HBMWD
Pipeline (oblique)	1960-92	32	25.0	5.8	500	2885	0.18	HBMWD
299 Bridge	1960-92	32	13.1	6.1	251	1523	0.19	HBMWD
Hwy 299 Bridge East Span	1941-60	29	11.1	8.8	300	2640	0.30	CalTrans
	1960-72	12	5.5	4.3	300	1290	0.36	
	1972-91	19	7.0	3.5	300	1050	0.18	
	1960-91	31	12.0	7.8	300	2340	0.25	
	1941-91	50	22.1	16.6	300	4980	0.33	
Hwy 299 Bridge West Span partial survey	1960-91	31	12.3	8.4	299	2512	0.27	CalTrans
	1991-92	1	1.9	0.0	254	0	0.00	
Hwy 299 Bridge West Span	1960-91	31	13.7	7.8	294	2293	0.25	Lehre/CalTrans
Hwy 101 Bridge East Span	1929-57	28	13.9	9.7	233	2252	0.35	CalTrans
	1957-72	15	8.5	5.2	233	1214	0.35	
	1972-89	17	1.5	0.2	233	45	0.01	
	1957-89	32	7.7	5.4	233	1260	0.17	
	1929-89	50	17.0	15.1	233	3511	0.30	
Hwy 101 Bridge East Span	1957-91	34	6.7	4.1	228	935	0.12	Lehre/CalTrans
Hwy 101 Bridge West Span	1957-72	15	9.3	4.2	229	968	0.28	CalTrans
	1972-89	17	2.6	0.5	229	125	0.03	
	1957-89	32	8.2	4.8	229	1093	0.15	

Volume of bed erosion since 1960

To estimate the volume of material removed from the Mad River by bed erosion, I divided the channel into four relatively homogeneous reaches (Hatchery to Blue Lake Bridge, Blue Lake Bridge to Railroad Bridge, Railroad Bridge to Hwy. 299, and Hwy. 299 to Hwy 101). Trinity Restoration Associates delineated and digitized the boundaries of the active channel on blowups of airphotos taken in 1954, 1988, and 1992, and provided me with estimates of channel area for each reach (Table 3.9). I estimated the volume of material lost from each by multiplying the area of each reach by the average of the mean lowering rates at each end. These computations are shown in Table 3.10. Approximately 5.5 million cubic yards of material were removed by bed lowering in the period 1962-1992, or about 185,000 cubic yards per year.

Table 3.9 -- Areas of active channel, 1954-1992

	Area of Active Channel, ft ²				Total
	Hatchery to Blue Lake Br	Blue Lake Br to Railroad Br	Railroad Br to Hwy 299 Br	Hwy 299 Br to Hwy 101 Br	
1954	4,773,000	15,980,000	4,299,000	6,195,000	31,247,000
1988	6,451,000	16,575,000	3,867,000	4,562,000	31,455,000
1992	4,410,000	11,161,000	3,897,000	4,331,000	23,799,000
mean	5,211,333	14,572,000	4,021,000	5,029,333	28,833,667

Table 3.10 -- Mad River bed erosion volumes, 1962-1992

Note: To reduce round-off error when summing and averaging, quantities in Table 3.10 are given to more significant figures than justified; individual values should be rounded to the nearest ten-thousand before citation or use.

Reach	Mean Active Channel Area ft ²	Lowering Rate Upper End ft/yr	Lowering Rate Lower End ft/yr	Mean Lowering Rate ft/yr	Volume removed ft ³	Volume removed yd ³
Hatchery to Blue Lake Br	5,211,333		0.18	0.18	28,141,200	1,042,267
Blue Lk Br to Railroad Br	14,572,000	0.18	0.12	0.15	65,574,000	2,428,667
Railroad Br to Hwy 299 Br	4,021,000	0.12	0.26	0.19	22,919,700	848,878
Hwy 299 Br to Hwy 101 Br	5,029,333	0.26	0.16	0.21	31,684,800	1,173,511
Total (1962-1992)	28,833,667	—	—	—	148,319,700	5,493,322
Yearly average (1962-1992)	—	—	—	—	4,943,990	183,111

Bed sediment budget for the Mad River channel between hatchery and Highway 101

Comparison of recruitment and extraction volumes: A simple but instructive bed sediment budget for the lower Mad River channel can be developed by comparing the mean annual volume of bedload recruitment to that removed by gravel mining. Based on data supplied by individual gravel extractors and the U.S. Bureau of Mines, the *minimum* volume of gravel removed from the reach since 1960 is about 13.6 million cubic yards (Table 3.11, Figs. 3.6 and 3.7), or an average of 425,000 yd³/year. My best estimate of long-term *average* annual recruitment is about 150,000 yd³/yr, with 200,000 yd³/yr an upper limit. This indicates that, on the average, somewhere between 225,000 to 275,000 yd³/yr are removed *in excess of annual resupply*. (That is, sustained yield is being exceeded by 225,000 to 275,000 yd³/yr over the long term.) Note that this deficit is about the same size as the average annual bed degradation volume of 185,000 yd³/yr. This strongly suggests that gravel extraction substantially in excess of long term sustained yield is responsible for virtually all of the of the bed lowering observed in the past 30 years. These computations are summarized in Table 3.12.

Comparison of bedload transport rates at Arcata and Blue Lake: Comparison of measured bedload transport at the Arcata (Hwy. 299) and Blue Lake (hatchery) gages provides a second means for assessing the relation of gravel extraction to bed lowering. Using Brown's (1975) bedload rating curves, estimated 1962-1992 mean annual bedload discharge is 127,000 yd³/yr at Blue Lake and 31,000 yd³/yr at Arcata (Table 3.3). Thus, if these estimates can be trusted, some 96,000 yd³/yr is "lost" between the hatchery and Highway 299 -- removed from bedload transport by bed aggradation (deposition), particle breakdown, or gravel extraction.

Between the hatchery and Highway 299, 1962-1992 mean annual gravel extraction was a minimum of 233,000 yd³/yr (data from Table 1.1). For the same period, bed lowering upstream of Highway 299 yielded 144,000 yd³/yr (Table 3.10). The difference between volume extracted and that accounted for by bed lowering in the reach -- 89,000 yd³/yr -- *must* be supplied by new recruitment from upstream.

Thus gravel extraction would not only account for *all* the observed bed lowering, but would also cause annual gravel transport at Highway 299 to be about 89,000 yd³/yr less than that at the hatchery. This is virtually identical to the 96,000 yd³/yr difference obtained from Brown's (1975) data.

Comparison of cumulative extraction and bed lowering: Finally, additional proof that bed lowering is strongly connected to gravel extraction is provided by Fig. 3.8. Here I have plotted cumulative bed lowering measured at the 299 and 101 bridges against cumulative gravel extraction upstream. The nearly straight-line relationship between extraction and bed lowering at the 299 bridge is quite striking, and strongly suggests that the two are causally linked.

Further downstream at the 101 bridge, Fig. 3.8 and the data in Tables 3.8 and 3.12 suggest that 1) little coarse bed material currently reaches the site -- it is all removed upstream; and 2) after 1972 the gradient had been flattened enough that little further bed erosion was able to occur, even though the stream was starved for sediment. This hypothesis is consistent with field observations that the bed at the 101 bridge is weedy and covered with finer sediment.

Table 3.11 -- Mad River bed lowering and cumulative gravel extraction, 1957-1992

Note: To reduce round-off error when summing and averaging, quantities in Table 3.11 are given to more significant figures than justified; individual values should be rounded to the nearest ten-thousand before citation or use.

year	cum volume extracted abv 299 since 1952 yd ³	cum volume extracted abv 299 since 1960 yd ³	cum mean lowering at 299 ft	cum volume extracted below 299 since 1952 yd ³	cum volume extracted below 299 since 1957 yd ³	total cum volume extracted since 1952 yd ³	cum total volume extracted since 1957 yd ³	cum mean lowering at 101 ft
1957	570,000			617,030	0	1,187,030	0	0.0
1960	905,000	0	0.0	1,088,272	471,242	1,993,272	806,242	
1972	3,953,499	3,048,499	4.3	4,627,731	4,010,701	8,581,230	7,394,200	5.2
1989	7,487,094	6,582,094		7,331,104	6,714,074	14,818,198	13,631,168	5.7
1991	7,926,105	7,021,105	7.8	7,508,884	6,891,854	15,434,989	14,247,959	
1992	8,078,722	7,173,722	7.8	7,508,884	6,891,854	15,587,606	14,400,576	

Table 3.12 -- Simple sediment budget for Mad River channel between hatchery and Hwy. 101

mean annual recruitment yd ³ /yr	mean annual extraction yd ³ /yr	recruitment - extraction yd ³ /yr	mean bed lowering yd ³ /yr
150,000 (best est)	425,000	-275,000	185,000
200,000 (max est)	425,000	-225,000	185,000

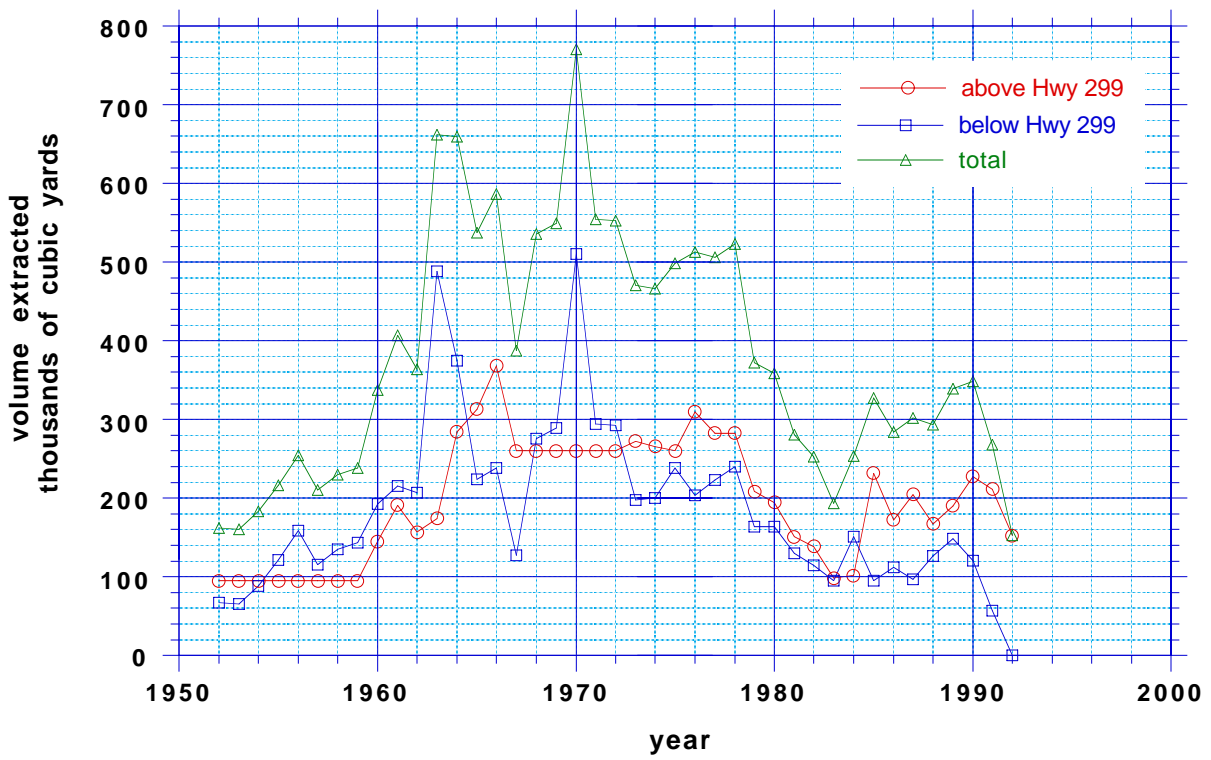


Fig. 3.6 -- Minimum yearly gravel extraction on the Mad River, 1952-1992

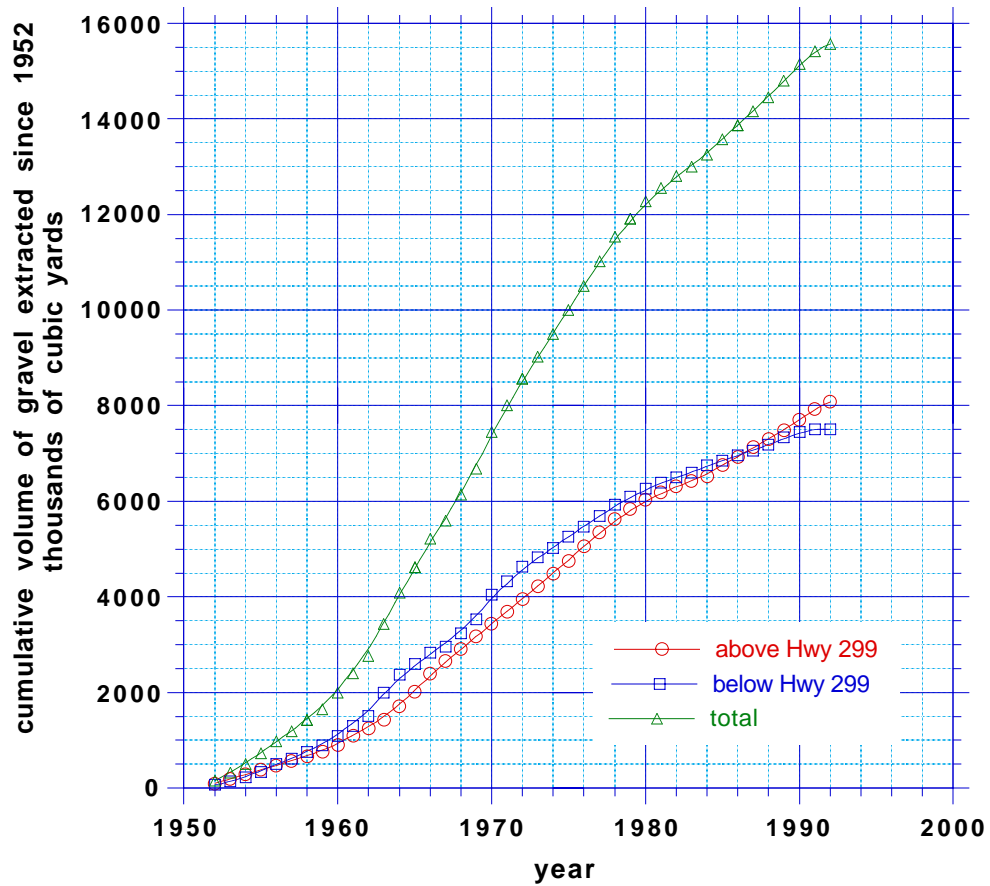


Fig. 3.7 -- Cumulative minimum gravel extraction from the Mad River 1952-1992

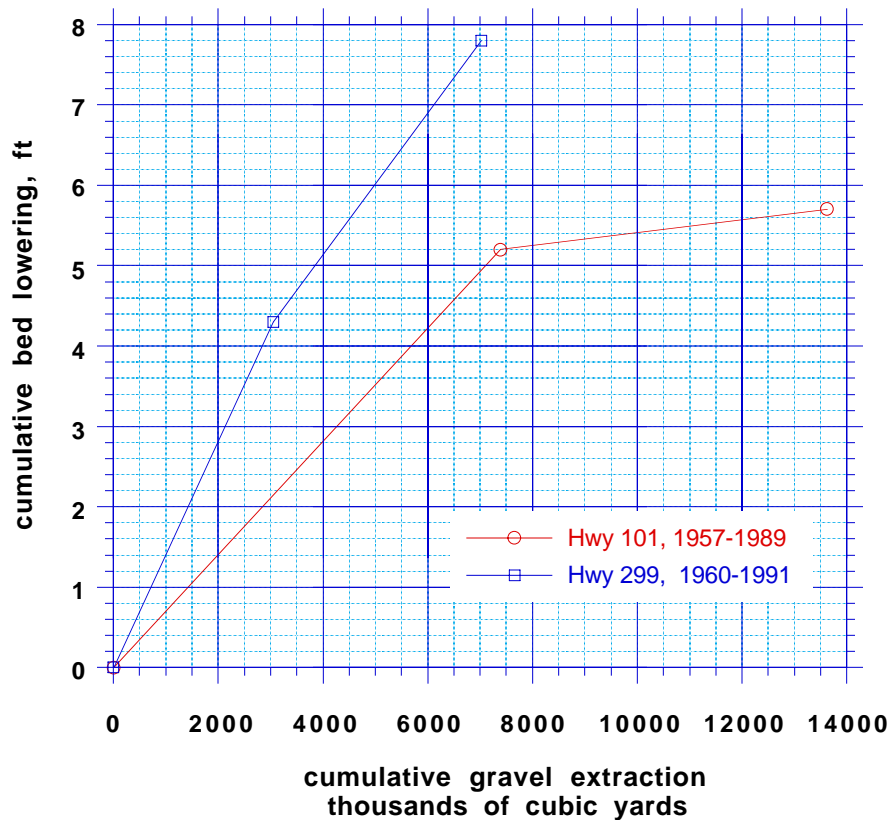


Fig. 3.8-- Cumulative bed lowering vs. cumulative gravel extraction on the Mad River since 1957. Relation is based on data in Table 3.11.

MANAGEMENT IMPLICATIONS

The recruitment study and analysis of bed degradation strongly suggest that the lowering of the Mad River channel observed over the last thirty years is not some short-term phenomenon related to the recent drought, but rather the response of the channel to the long-term and persistent removal of gravel in excess of what the river can resupply from upstream. The study suggests that long-term mean annual recruitment is probably less than 150,000 yd³/yr, with 200,000 yd³/yr certainly a maximum. Average annual removal by gravel extractors over the past thirty years is a *minimum* of 425,000 yd³/yr; the deficit has resulted in continued bed lowering. The bed will continue to degrade as long as extractions generally outpace resupply, or until the channel 1) encounters resistant underlying bedrock or 2) reduces its gradient to the point where it is incapable of effectively transporting coarse bedload. None of these are particularly desirable alternatives, either from the standpoint of extractors, those interested in river ecology, or other river users such as CalTrans and HBMWD.

We can see the first instance, degradation to bedrock or underlying more resistant materials, beginning to occur around the Hwy. 299 bridge. Large rocks have started to poke up out of the channel above the bridge, the bridge footings are being undermined, and older, silt-and-clay rich sediments are beginning to be exposed in the vicinity of the Johnson-Spini bar, making extraction there less desirable.

The second instance, reduction of gradient to one where little transport of coarse sediment occurs, appears to have happened at the 101 bridge. Between 1929 to 1972 the riverbed there dropped an average of ten feet. Since 1972 it has lowered only 0.2 - 0.5 foot. The river there is pool-like at low flow and fine sediment and aquatic plants cover the bottom. It is possible that the rapid northward migration of the Mad River mouth and the concomitant growth of the estuary may be in due, at least in part, to lack of recruitment of sufficient sediment from upstream. The sediment budget and observations at Hwy. 101 suggest that little coarse sediment is making it way to the mouth. The implications of this need to be investigated.

Bed lowering has already compromised the seismic stability of bridges crossing the Mad River and bridge footings are being undermined or exposed and will require replacement or remedial work (Dennis McBride, pers. communication). Bed lowering in the HBMWD reach has threatened the usability of Pump Station 6, and the reduced gravel thickness over the Ranney collectors reduces natural filtration. Continued bed lowering will only make matters worse. Thus it would seem prudent to manage gravel extraction in such a way that it does not exceed annual recruitment.

I wish to emphasize that bed lowering is a persistent, long-term phenomenon related to long-term average replenishment and extraction rates, and for sustained yield the river must be managed on that basis. Great fluctuations in supply may occur from year to year, depending on whether we have droughts or floods, but in the long term, lean years will be balanced by fat years and vice versa. A long-term mean annual extraction volume could be set, and extractors would have to manage their operations to live within that. It would be reasonable to mine more than the annual recruitment in a dry year, realizing though that this would mean that in a wet year merchantable gravel would have to be left behind in compensation. Such a strategy would provide an even flow to extractors, while preventing continued bed lowering. Bed elevations might fluctuate from year to year, but if the long-term balance is kept there will be no net degradation.

If the river is to be kept in its current state, on the basis of current knowledge I recommend that mean total extraction on the Mad River not exceed 150,000 yd³/yr. If the management objective is not simply to maintain the status quo, but to induce aggradation (recovery of bed elevation) it would be reasonable to limit mean total extraction to no more than 100,000 yd³/yr. River bed elevations and cross-sections should be monitored. Long-term extraction targets could then be adjusted upwards or downwards depending upon the observed river response.

References Cited

- Bagnold, R.A., 1980, An empirical correlation of bedload transport rates in flumes and natural rivers: *Proc. Royal Society London, Series A*, v. 372, p. 453-473.
- Brown, William M. III, 1973, Streamflow, sediment, and turbidity in the Mad River Basin, Humboldt and Trinity Counties, California: *U.S. Geological Survey Water Resources Investigations 36-73*, 57 p.
- Brown, William M. III, 1975, Sediment transport, turbidity, channel configuration, and possible effects of impoundment of the Mad River, Humboldt County, California: *U.S. Geological Survey Water Resources Investigations 26-75*, 63 p.
- Carson, M.A. and G.A. Griffiths, Bedload transport in gravel channels: *Journal of Hydrology (New Zealand)*, v. 26 no. 1, p. 1-151.
- Collins, B. and T. Dunne, 1990, Fluvial geomorphology and gravel mining: a guide for planners, case studies included: *California Division of Mines and Geology Special Pub. 98*, 29 p.
- Davies, T.R.H., 1987, Problems of bed load transport in braided gravel-bed rivers: in C.R. Thorne, J.C. Bathurst, and R.D. Hey eds., *Sediment Transport in Gravel-Bed Rivers*, John Wiley & Sons, Chichester, p. 793-828.
- Dietrich, W.E. and J.D. Gallinatti, Fluvial geomorphology: in O. Slaymaker, ed., *Field Experiments and Measurement Programs in Geomorphology*, University of British Columbia Press, Vancouver, p. 169-220.
- Federal Emergency Management Agency, 1986, *Flood Insurance Study, Humboldt County, California Unincorporated Areas*, 45 p.
- Gomez, B. and M. Church, 1989, An assessment of bed load sediment transport formulas for gravel bed rivers: *Water Resources Research*, v. 25 no. 6, p. 1161-1186.
- Hubbell, D.W., 1987, Bed load sampling and analysis: in C.R. Thorne, J.C. Bathurst, and R.D. Hey eds., *Sediment Transport in Gravel-Bed Rivers*, John Wiley & Sons, Chichester, p. 89-118.
- Lisle, T.M. and M.A. Madej, 1992, Spatial variation in armouring in a channel with high sediment supply: in P. Billi, R.D. Hey, C.R. Thorne, and P. Tacconi eds., *Dynamics of Gravel-bed Rivers*, John Wiley & Sons, Chichester, p. 277 - 293.
- Reid, L.M. and T. Dunne, 1992, Rapid evaluation of sediment budgets : unpublished draft, to be published as a *U.S. Forest Service Pacific Southwest Research Station General Technical Report*, 169 p.
- Thompson, S.M., 1985, Transport of gravel by flows of up to 500 m³/s, Ohau River, Otago, New Zealand: *Journal of Hydraulic Research*, v. 23 no. 3, p. 285-305.
- Trinity Fisheries Consulting, 1990, Channel morphology description of a Mad River gravel bar: *report to Eureka Forest Products Inc., November 1990*, Arcata, 10 p.
- Vanoni, V.A., ed., 1975, *Sedimentation Engineering*: American Society of Civil Engineers, 745 p.
- White, W.R., H. Milli and A.D. Crabbe, 1973a, Sediment transport: an appraisal of available methods, vol. 1: Summary of existing theories: *Hydraulics Research Station Report No. INT 119*, Wallingford, England, 56 p.
- White, W.R., H. Milli and A.D. Crabbe, 1973b, Sediment transport: an appraisal of available methods, vol. 2: Performance of theoretical methods when applied to flume and field data: *Hydraulics Research Station Report No. INT 119*, Wallingford, England, 54 p.

**Addendum to Mad River EIR Technical Supplement Section 3:
Estimation Of Mad River Gravel Recruitment And Analysis Of Channel Degradation**

Prepared by Andre Lehre -- 22 December 1994

Estimation of bedload transport from filling of Sweasey Dam

An independent estimate of mean bedload transport rate in the Mad River is provided by the filling of Sweasey Dam. Sweasey Dam was constructed in 1938 to provide water supply for the city of Eureka. It was located about 5 mi upstream from the Blue Lake gage and impounded a 3,000 acre-foot reservoir (Brown, 1975, p. 47). The reservoir filled with sediment during floods in the 1950's, and was not functional for water-supply purposes by the early 1960's (Brown, 1975). The dam was removed by dynamiting in August, 1970. According to Brown (1975, p. 49) more than 2,000 acre-feet of sediment, mostly gravel and sand, was deposited behind the dam.

The mean annual bedload transport rate at Sweasey Dam can be computed by dividing the volume of sediment behind the dam by the number of years it took to fill. A maximum transport rate can be estimated by assuming that the entire reservoir capacity was filled and that filling was complete by 1960. A minimum transport rate can be calculated by assuming that only 2,000 acre-feet of the reservoir were filled and that filling was not complete until 1970. These bedload transport estimates are given in the table below.

Addendum Table 1 -- Bedload transport estimates from filling of Sweasey Dam

estimate	fill volume acre-feet	fill volume yd ³	time span	fill time yr	transport rate yd ³ /yr	transport rate tons/yr
maximum	3000	4,840,000	1938 - 1960	22	220,000	308,000
intermediate	3000	4,840,000	1938 - 1970	32	151,000	212,000
minimum	2000	3,230,000	1938 - 1970	32	101,000	141,000

Between Sweasey Dam and the Blue Lake gage, only one significant tributary, Canon Creek, enters. The amount of bedload it contributes to the system is unknown, but an estimate of its *maximum* possible contribution can be obtained by assuming that *all* the difference in bedload between the Kneeland and Blue Lake gages comes from Canon Cr. From the estimates in Table 3.6, this amounts to about 47,000 yd³/yr. Since the drainage area of Canon Cr occupies about half of the area between the Kneeland and Blue Lake gages, a more reasonable estimate of its contribution might be 25,000 yd³/yr.

The estimates of bedload recruitment derived earlier in this report (e.g., Table 3.6; p. 15) were on the order of 100, 000 - 200,000 yd³/yr. The estimates derived from the filling of Sweasey Dam are in the same range: 101,000 - 220,000 yd³/yr for the reservoir alone, and 125,000 - 245,000 yd³/yr if Canon Cr is included.

Section 3 Appendix: Cross-sections used in calculation of bed degradation

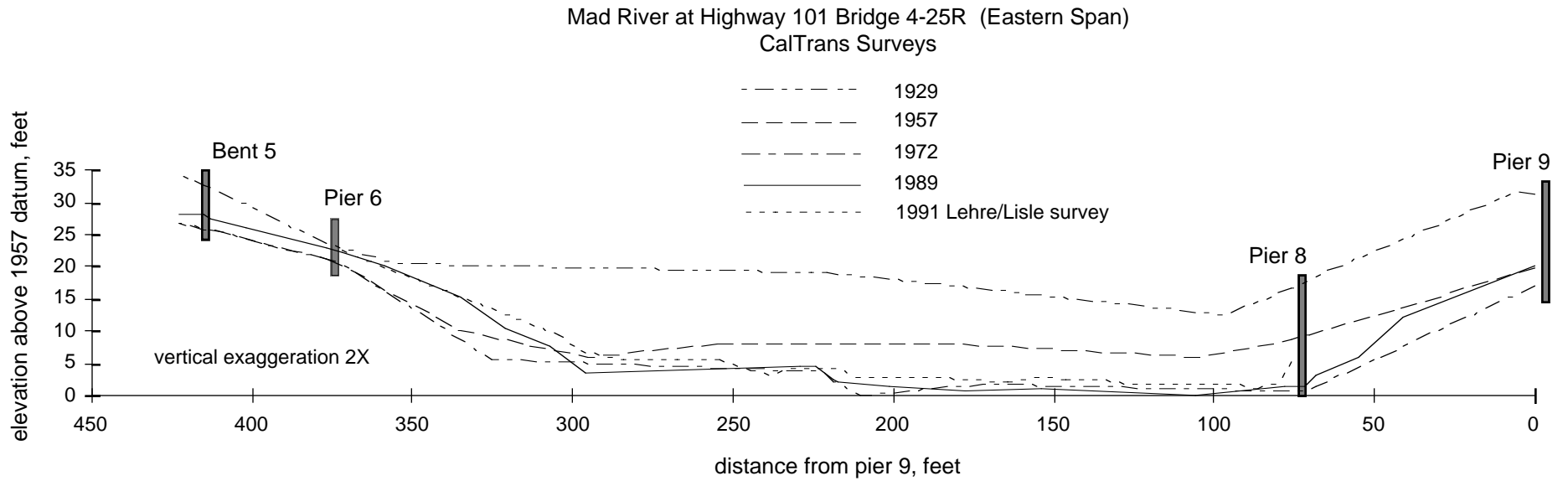
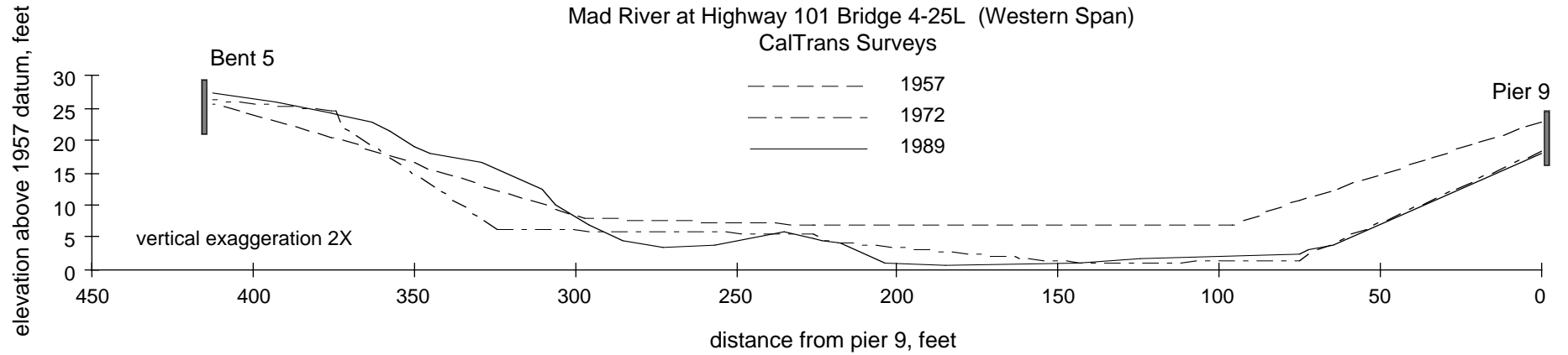


Fig. 3.A1 -- Cross-sections of the Mad River at Highway 101 bridge

View is downstream.

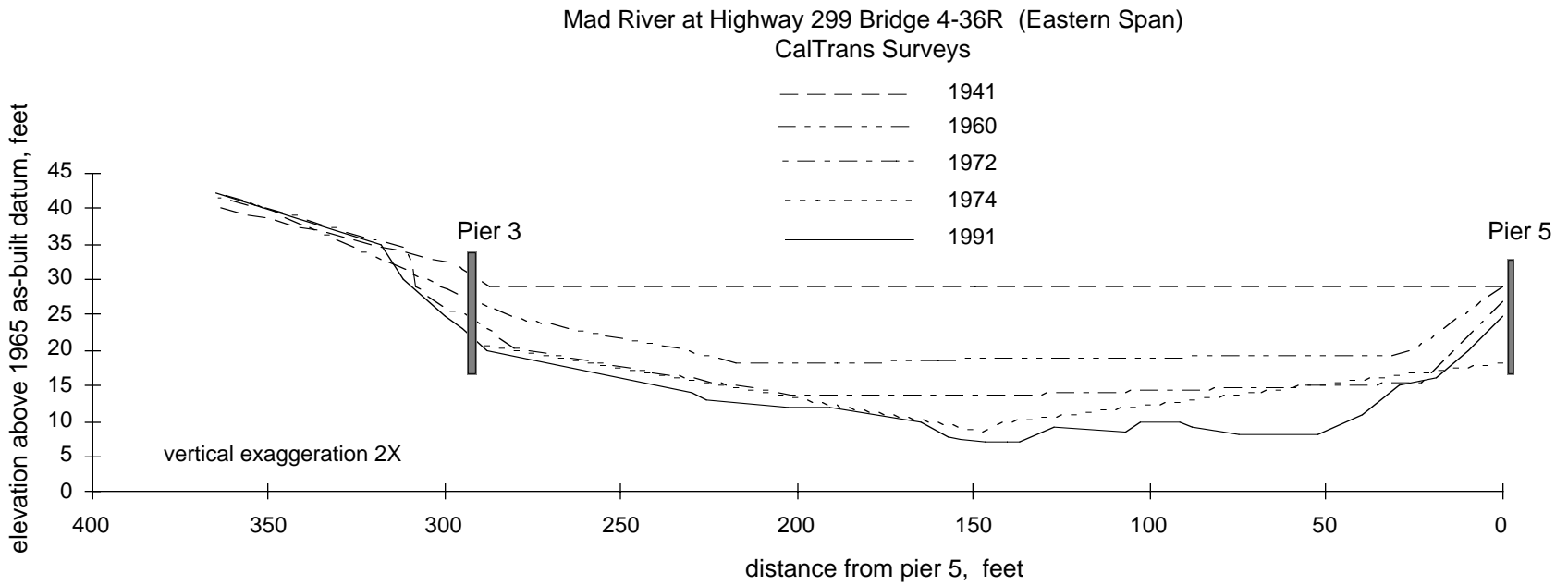
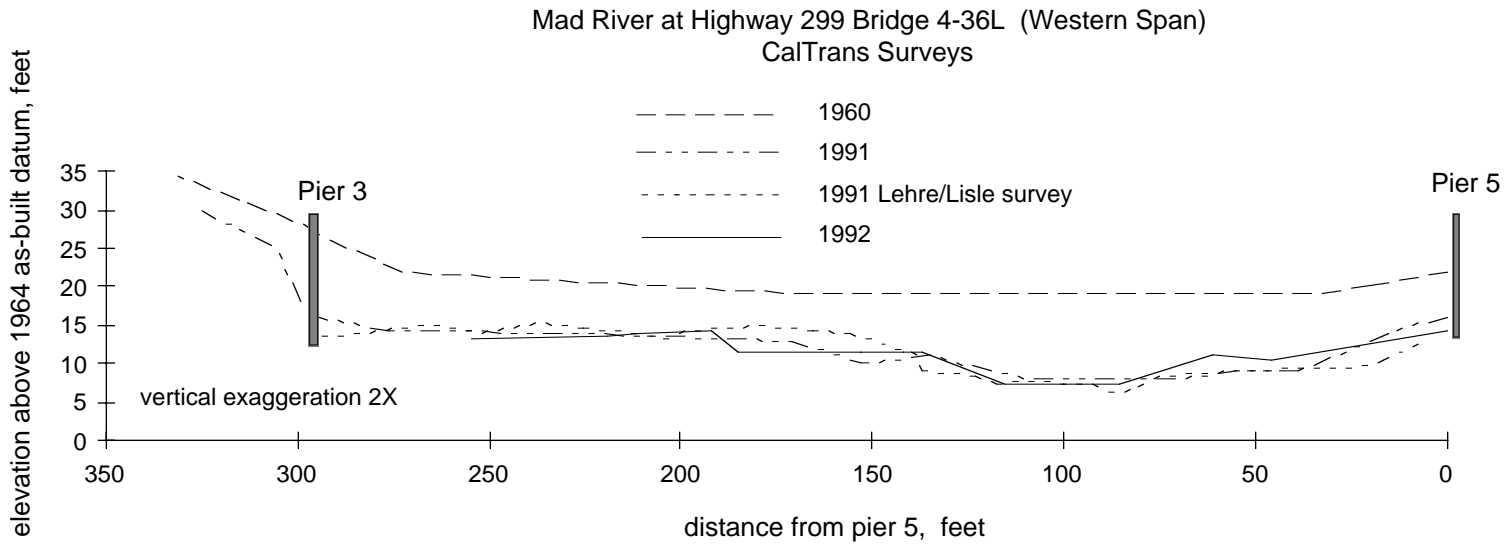


Fig. 3.A2 -- Cross-sections of the Mad River at Highway 299 bridge

View is downstream.

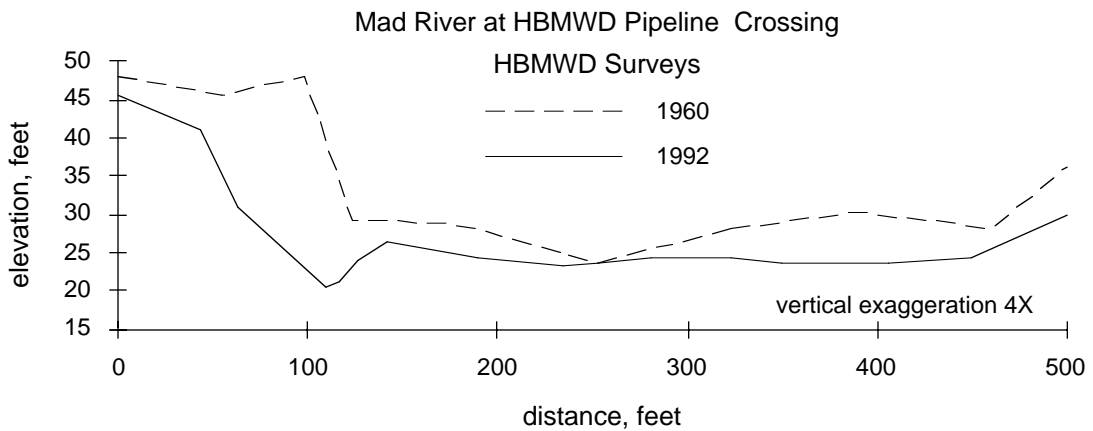
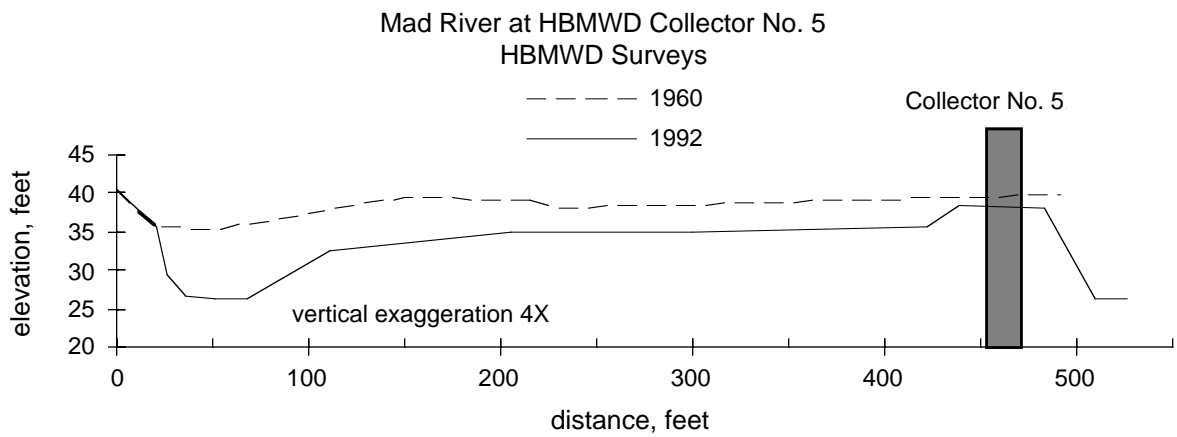
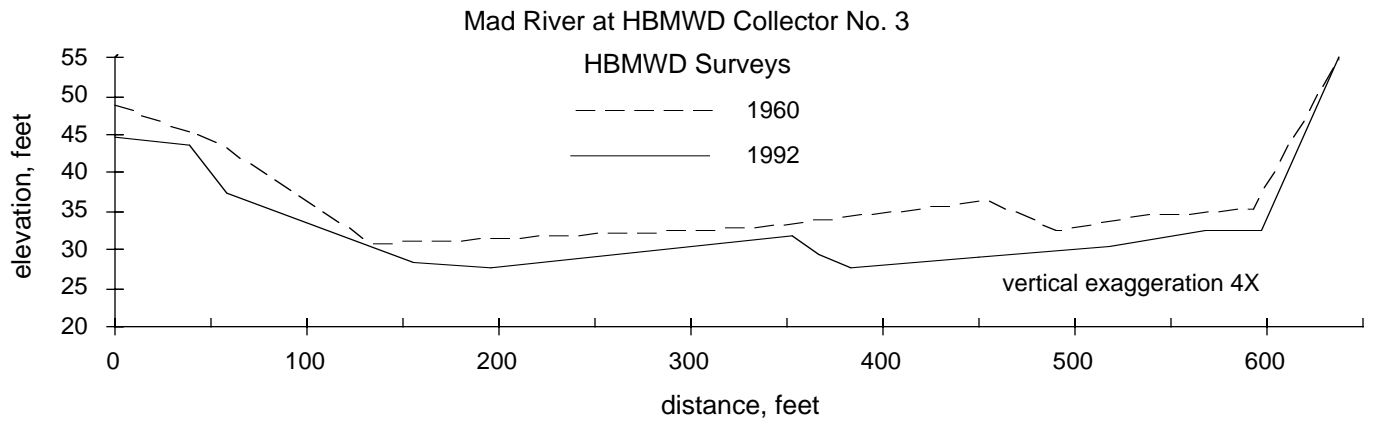


Fig. 3.A3 -- Cross-sections of the Mad River in the HBMWD reach

View is downstream.

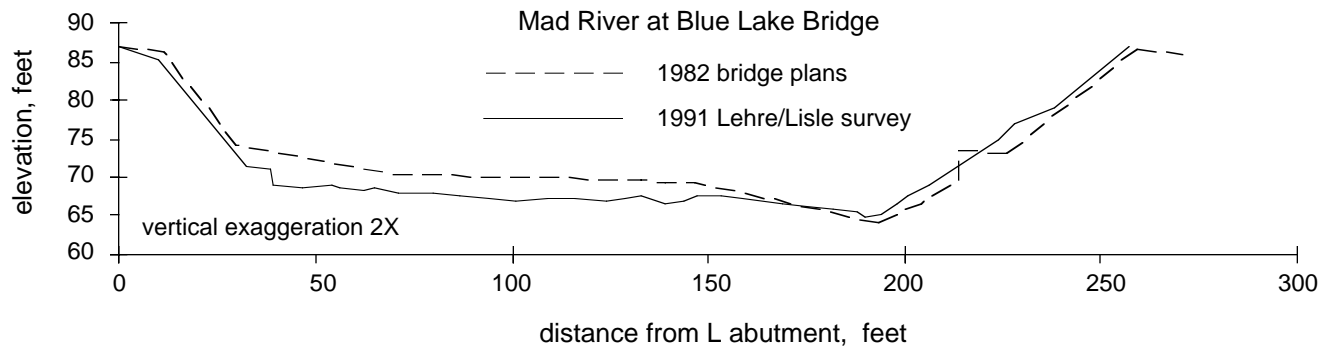


Fig. 3.A4 -- Cross-sections of the Mad River at Blue Lake (Hatchery Road) Bridge
View is downstream.