Appendix F

River Institute
Consultants Report

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

5 April 1993

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

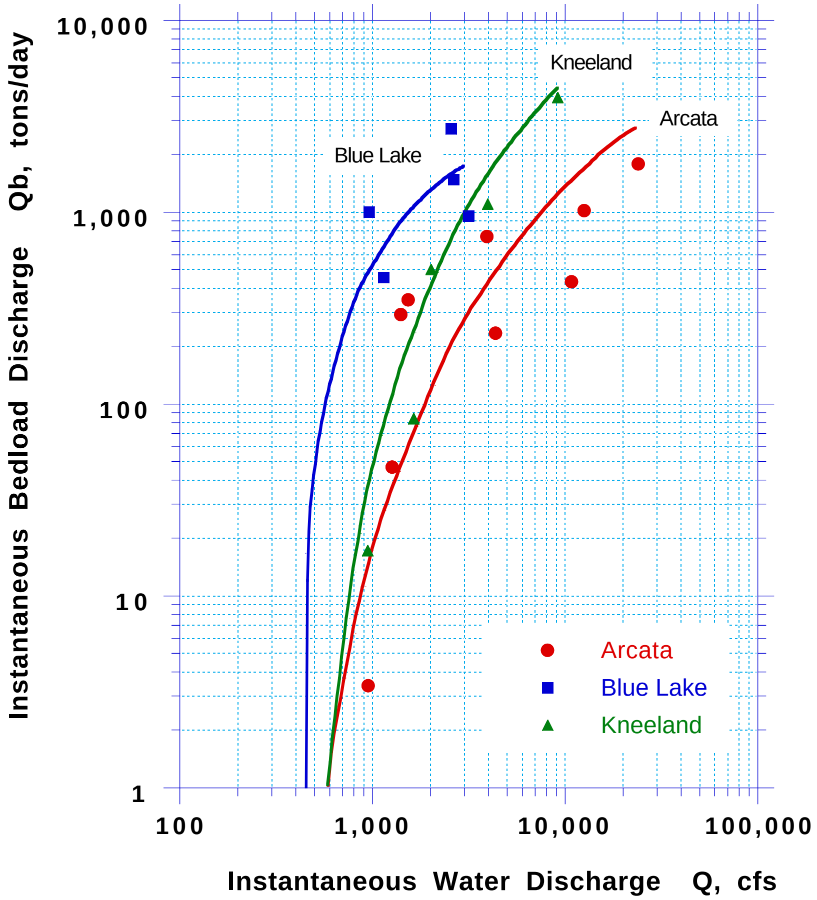


Fig. 3.1 --Bedload transport curves and data for the Mad River at Arcata, Blue Lake, and Kneeland, digitized from Brown (1975)

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.)

	Estimated Bedload Discharge, tons			Estimated Bedload Discharge, cu. yd.		
WY	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

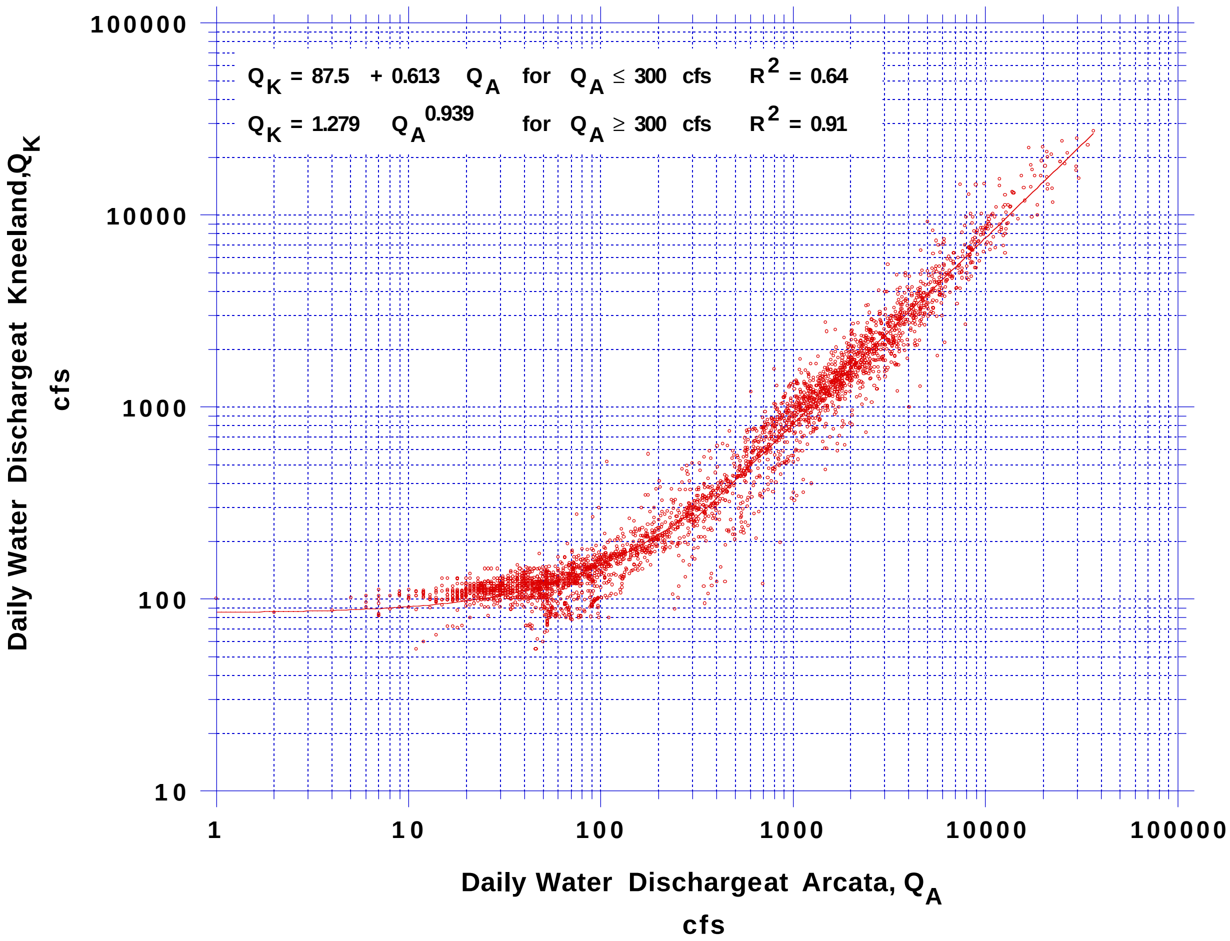


Fig. 3.2 -- Correlation of daily water discharge at Kneeland with daily water discharge at Arcata for WY 1966-1974.

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.

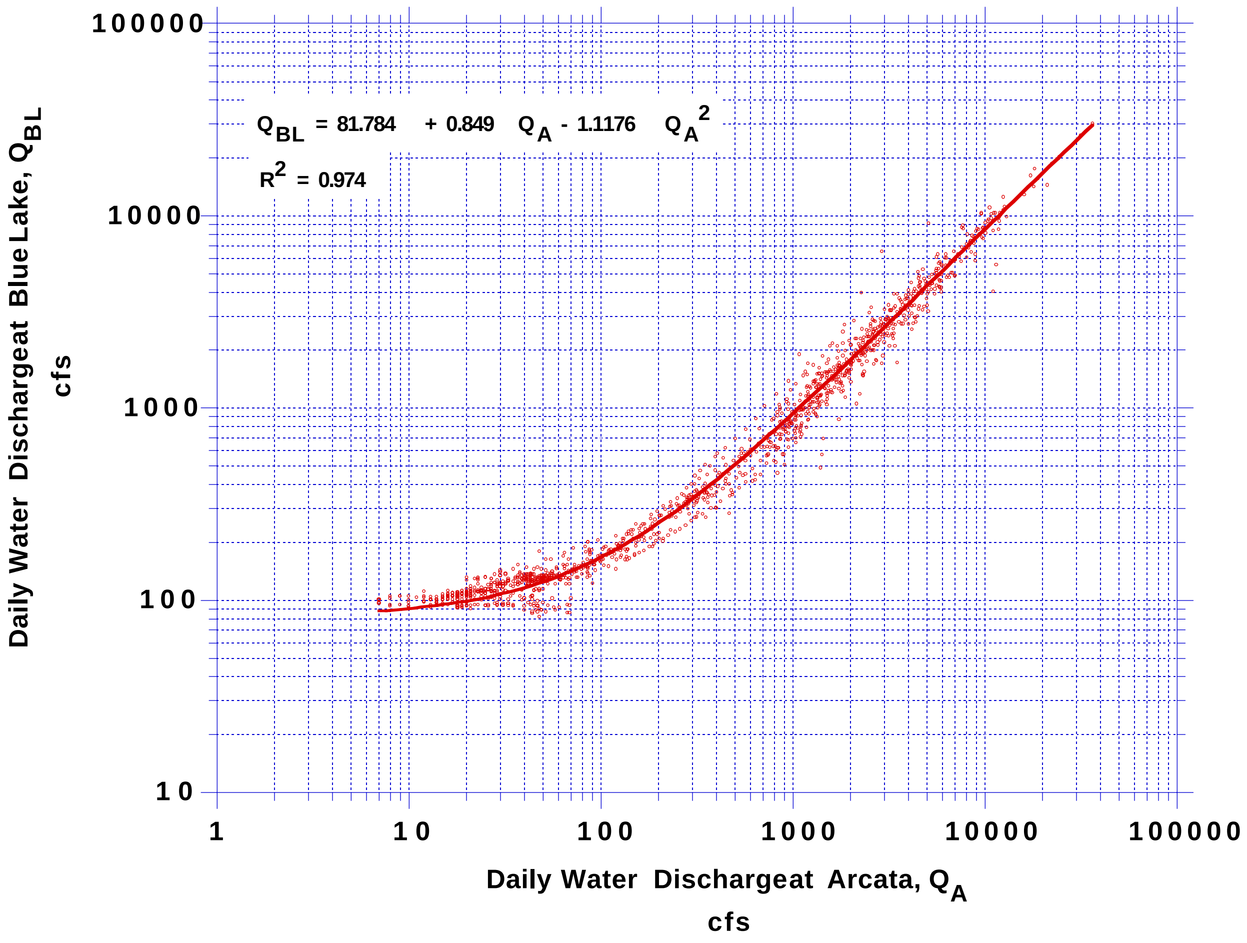


Fig. 3.3 -- Correlation of daily water discharge at Blue Lake with daily water discharge at Arcata for WY 1972-1976.

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 ±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 yd^3/yr) at Arcata to a high of 178, 000 tons/yr (127,000 yd^3/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 yd^3) 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).

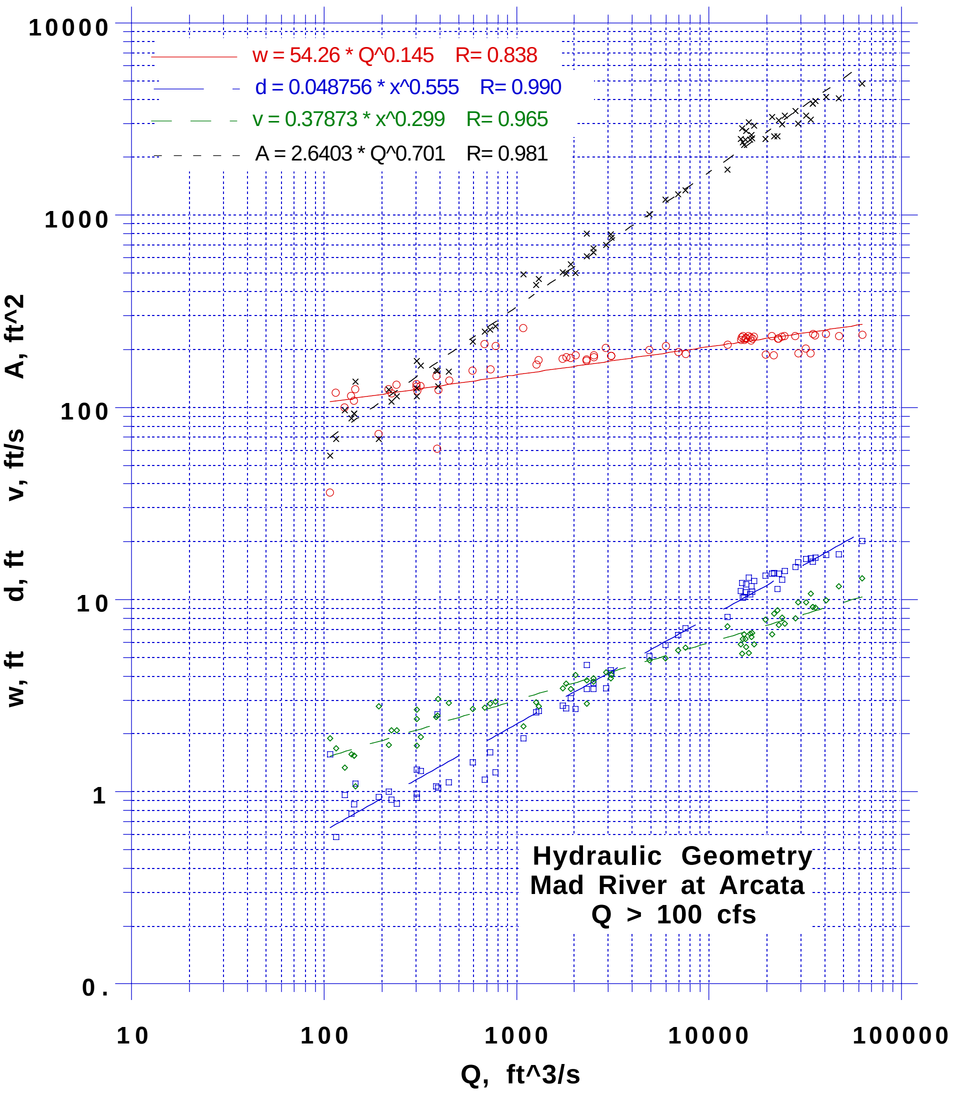


Fig 3.4 -- Hydraulic geometry at Arcata for discharges greater than 100 cfs

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	$w = 54.26\ Q^{0.145}$	$w = 34.2\ Q^{0.25}$ $Q \le 1200$ cfs $w = 2.88\ Q^{0.60}$ $Q > 1200$ cfs	$w = 8.00\ Q^{0.40}$ $Q \le 1000$ cfs $w = 56.8\ Q^{0.10}$ $Q > 1000$ cfs
depth	ft	$d = 0.049\ Q^{0.555}$	$d = 0.074\ Q^{0.44}$ $Q \le 1200$ cfs $d = 0.406\ Q^{0.20}$ $Q > 1200$ cfs	$d = 0.460\ Q^{0.20}$ $Q \le 1000$ cfs $d = 0.021\ Q^{0.65}$ $Q > 1000$ cfs
velocity	ft/s	$v = 0.379\ Q^{0.299}$	$v = 0.395\ Q^{0.31}$ $Q \le 1200$ cfs $v = 0.855\ Q^{0.20}$ $Q > 1200$ cfs	$v = 0.270\ Q^{0.40}$ $Q \le 1000$ 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

	mean bedload transport 1962-1992, tons/yr			mean bedload transport 1962-1992, yd^3/yr		
estimation procedure	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) then 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 yd^3/yr) with the Ackers-White equation at Arcata to a high of 1,269,000 tons/yr (906,000 yd^3/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 yd^3). 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 yd^3/yr) at these sites probably provide an upper bound on average annual resupply.

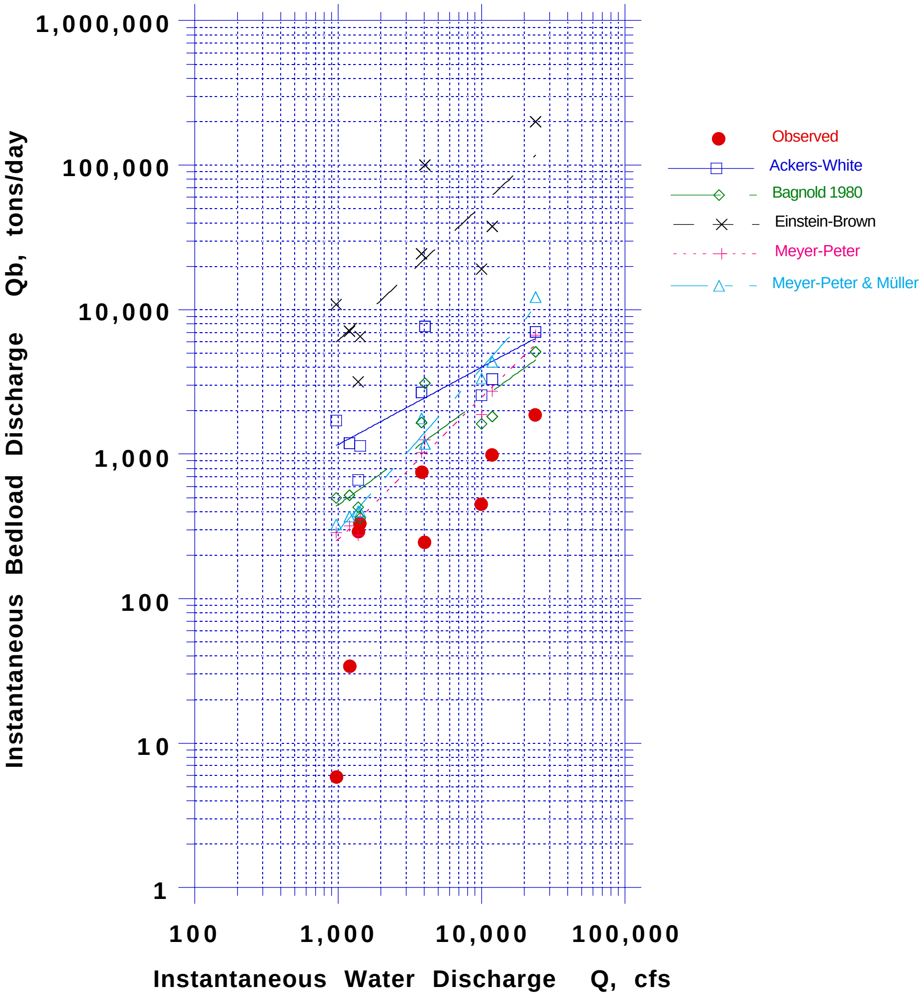


Fig. 3.5a -- Comparison of observed and predicted bedload transport rates at Arcata gage

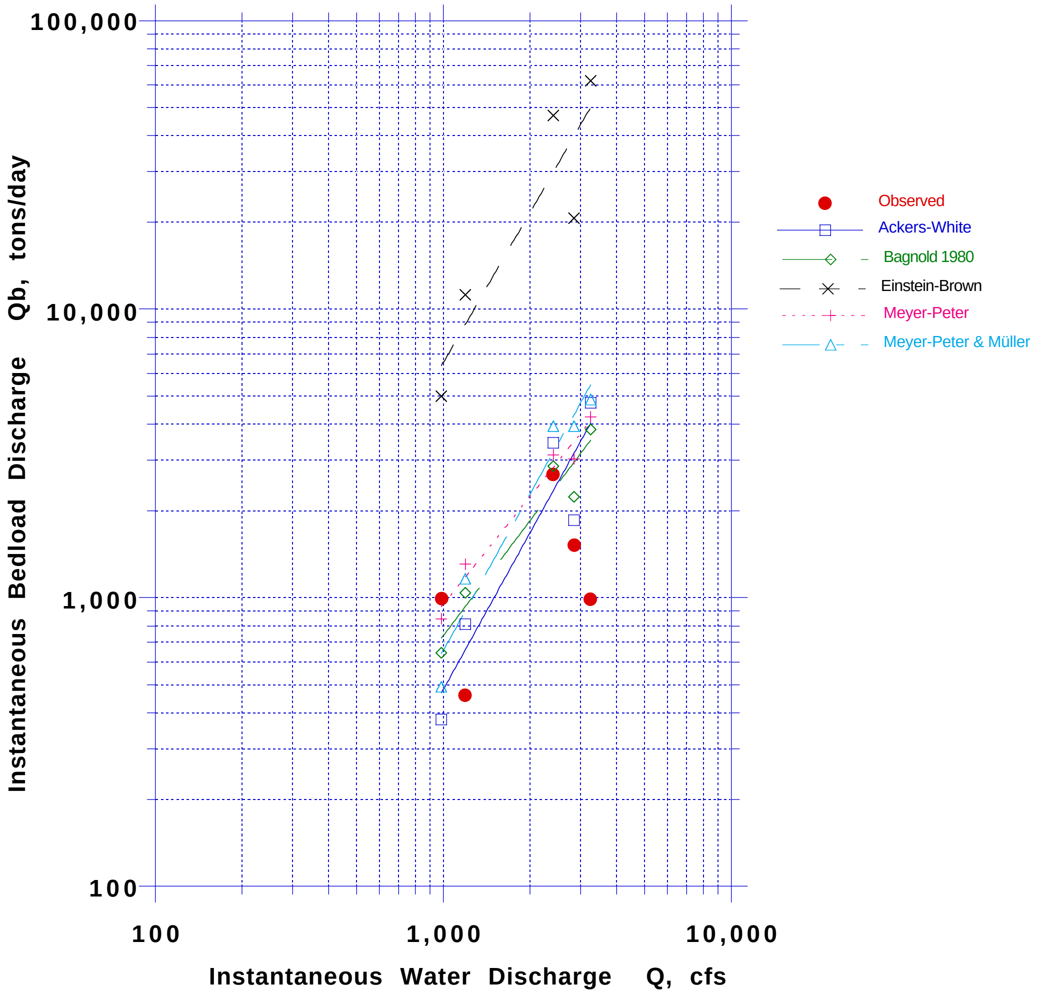


Fig. 3.5b -- Comparison of observed and predicted bedload transport rates at Blue Lake gage

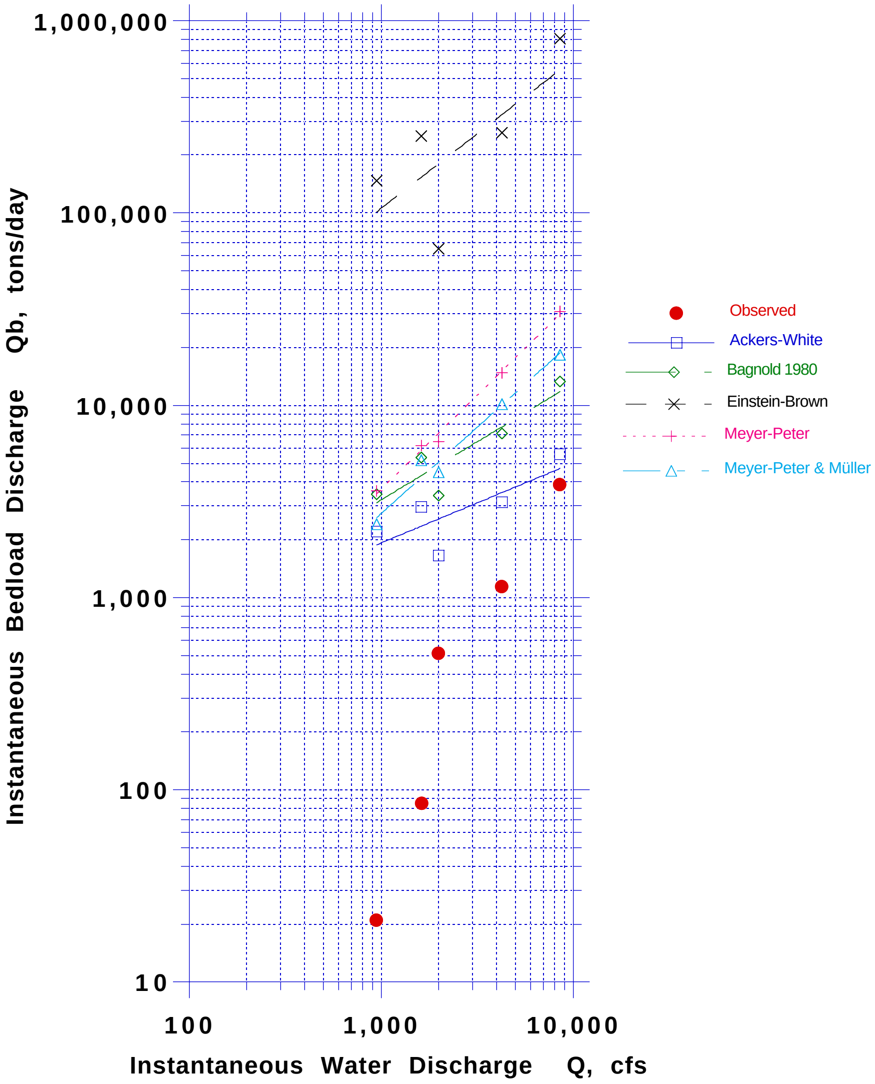


Fig. 3.5c -- Comparison of observed and predicted bedload transport rates at Kneeland gage

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 yd^3/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 yd^3/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.

	Estimated Suspended-Load Discharge, tons	
WY	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 yd^3/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 yd^3/yr). In my opinion, a reasonable estimate of mean annual recruitment for planning purposes is 150,000 yd^3/yr, with 200,000 yd^3/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	1960-91	31	12.3	8.4	299	2512	0.27	CalTrans
partial survey	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				
	Hatchery to Blue Lake Br	Blue Lake Br to Railroad Br	Railroad Br to Hwy 299 Br	Hwy 299 Br to Hwy 101 Br	Total
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 yd^3/year. My best estimate of long-term *average* annual recruitment is about 150,000 yd^3/yr, with 200,000 yd^3/yr an upper limit. This indicates that, on the average, somewhere between 225,000 to 275,000 yd^3/yr are removed *in excess of annual resupply*. (That is, sustained yield is being exceeded by 225,000 to 275,000 yd^3/yr over the long term.) Note that this deficit is about the same size as the average annual bed degradation volume of 185,000 yd^3/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 yd^3/yr at Blue Lake and 31,000 yd^3/yr at Arcata (Table 3.3). Thus, if these estimates can be trusted, some 96,000 yd^3/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 yd^3/yr (data from Table 1.1). For the same period, bed lowering upstream of Highway 299 yielded 144,000 yd^3/yr (Table 3.10). The difference between volume extracted and that accounted for by bed lowering in the reach -- 89,000 yd^3/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 yd^3/yr less than that at the hatchery. This is virtually identical to the 96,000 yd^3/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

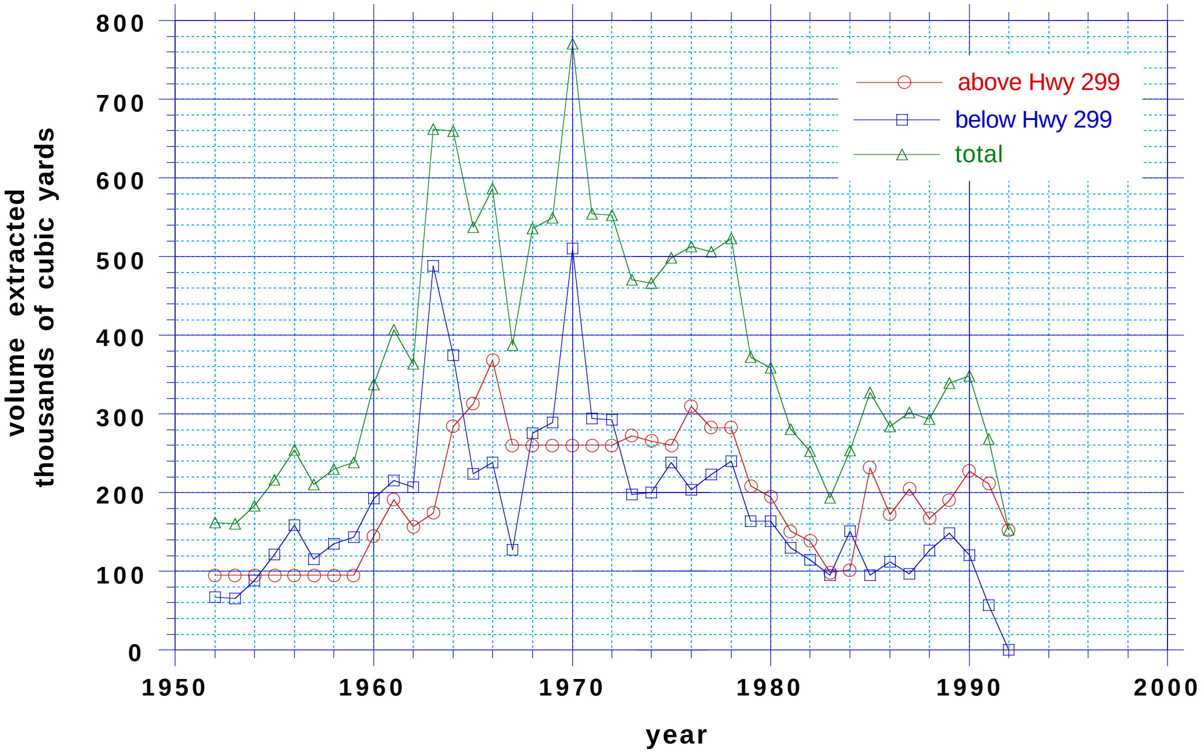


Fig. 3.6 -- Minimum yearly gravel extraction on the Mad River, 1952-1992

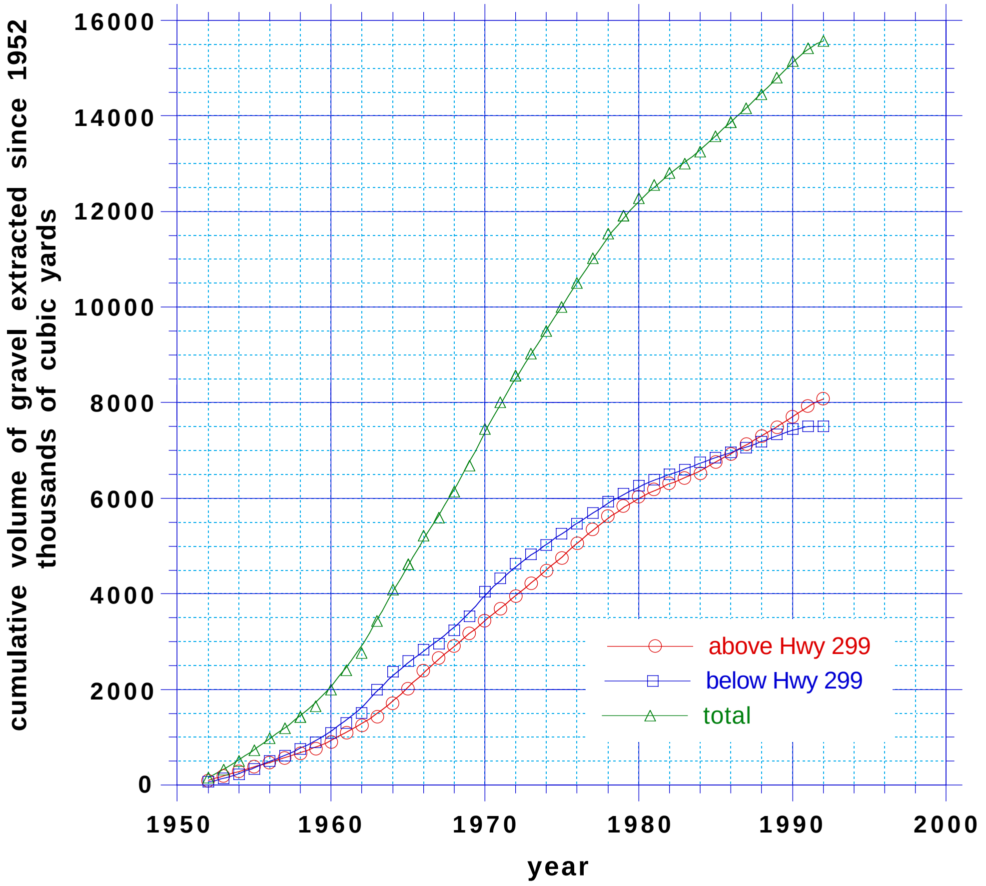


Fig. 3.7 -- Cumulative minimum gravel extraction from the Mad River 1952-1992

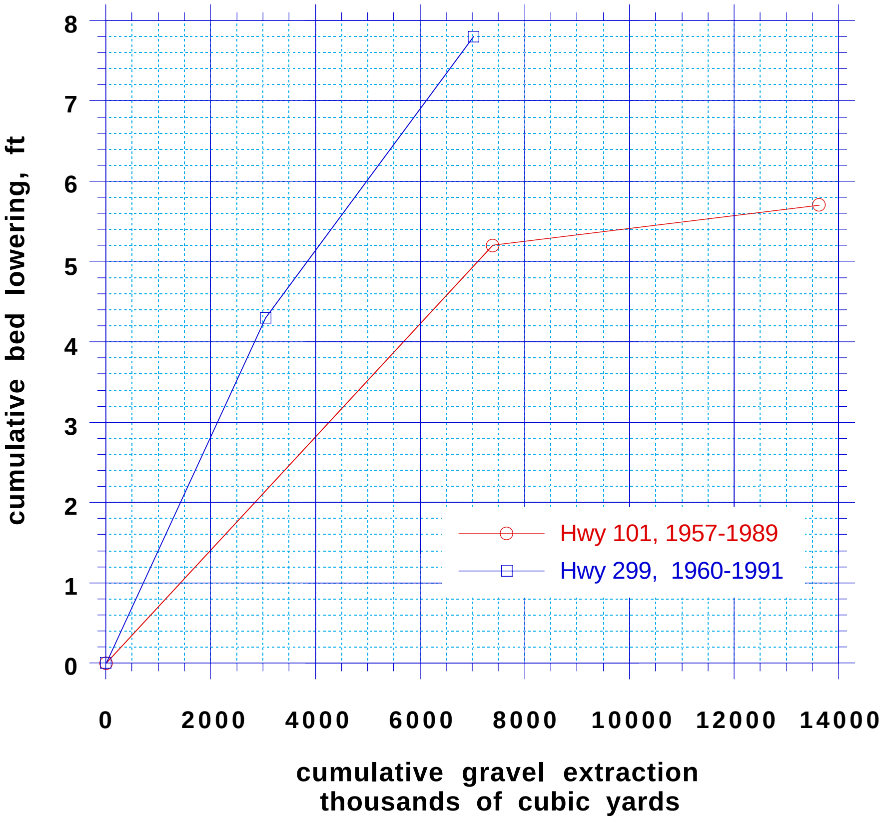


Fig. 3.8-- Cumulative bed lowering vs. cumulative gravel extraction on the Mad River since 1957. Relation is based on data in Table 3.11.

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 yd^3/yr, with 200,000 yd^3/yr certainly a maximum. Average annual removal by gravel extractors over the past thirty years is a *minimum* of 425,000 yd^3/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 yd^3/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 yd^3/yr. River bed elevations and cross-sections should 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 m^3/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 yd^3/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 yd^3/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 yd^3/yr. The estimates derived from the filling of Sweasey Dam are in the same range: 101,000 - 220,000 yd^3/yr for the reservoir alone, and 125,000 - 245,000 yd^3/yr if Canon Cr is included.

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

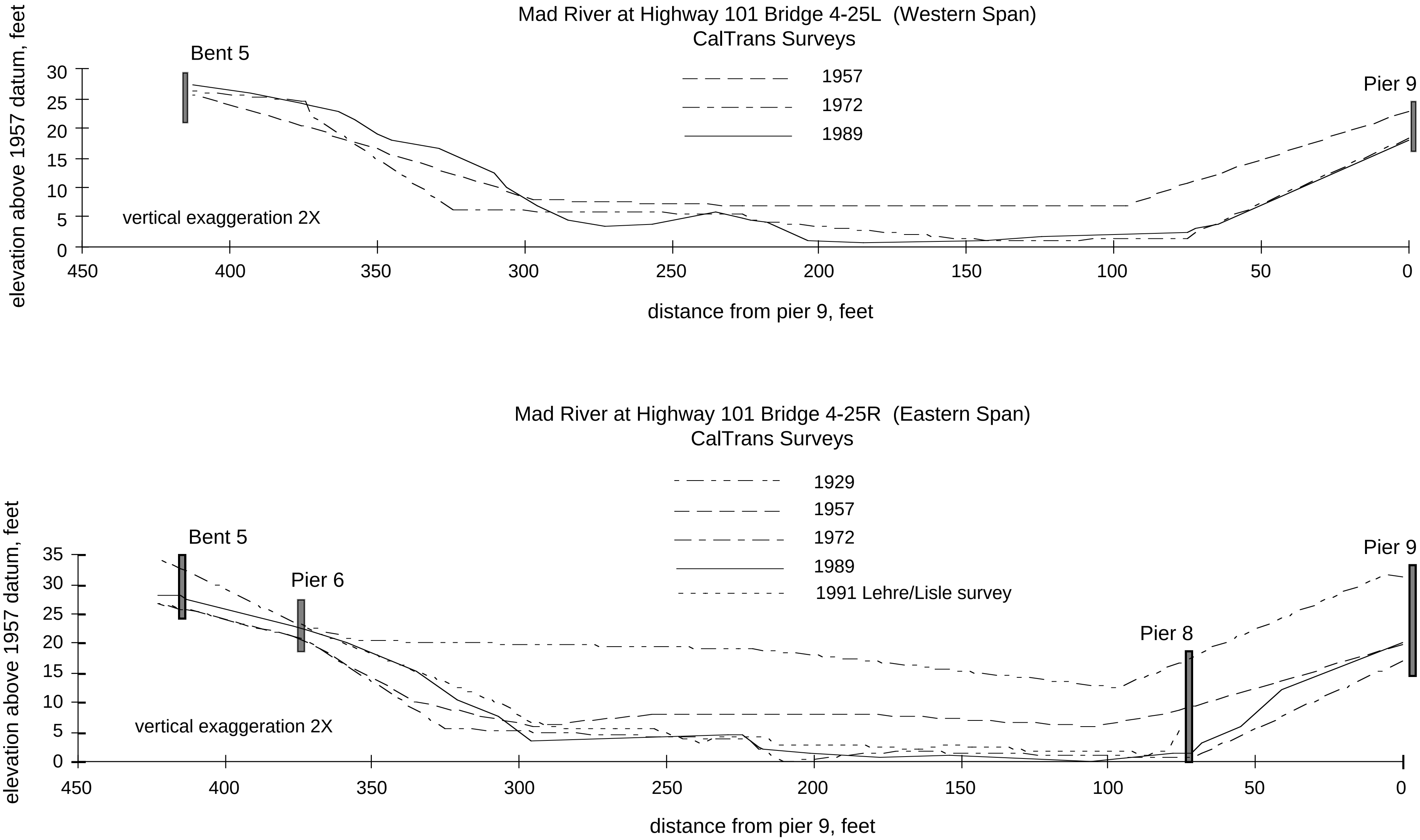
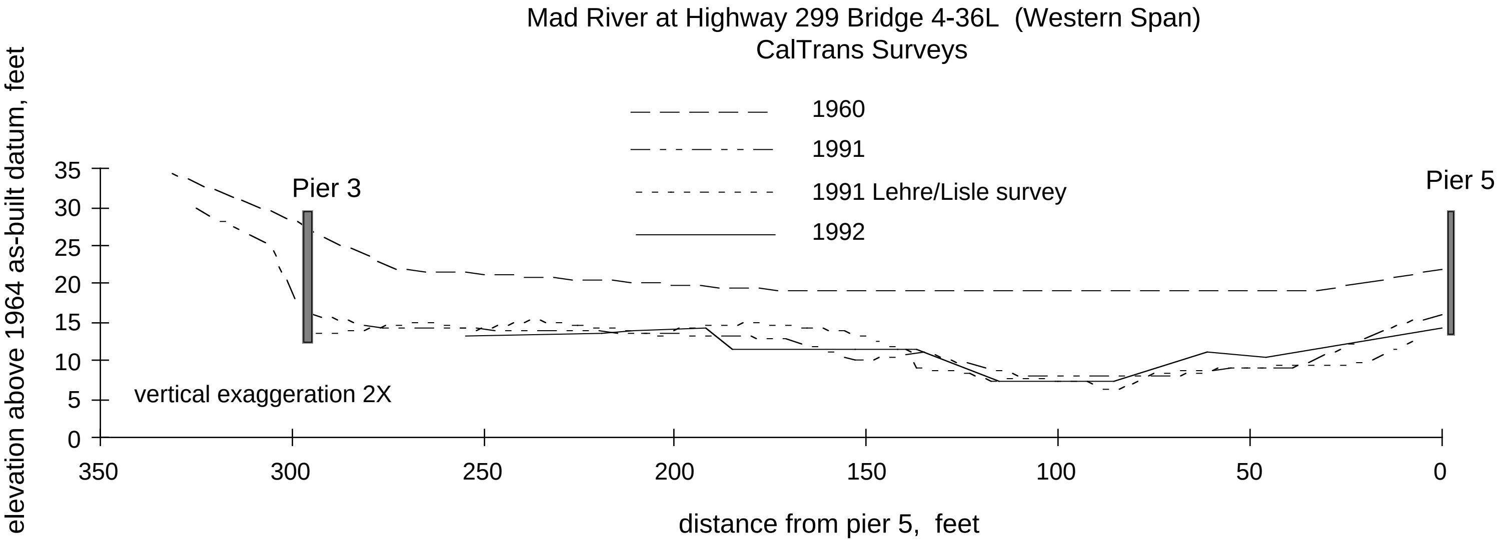


Fig. 3.A1 -- Cross-sections of the Mad River at Highway 101 bridge

View is downstream.



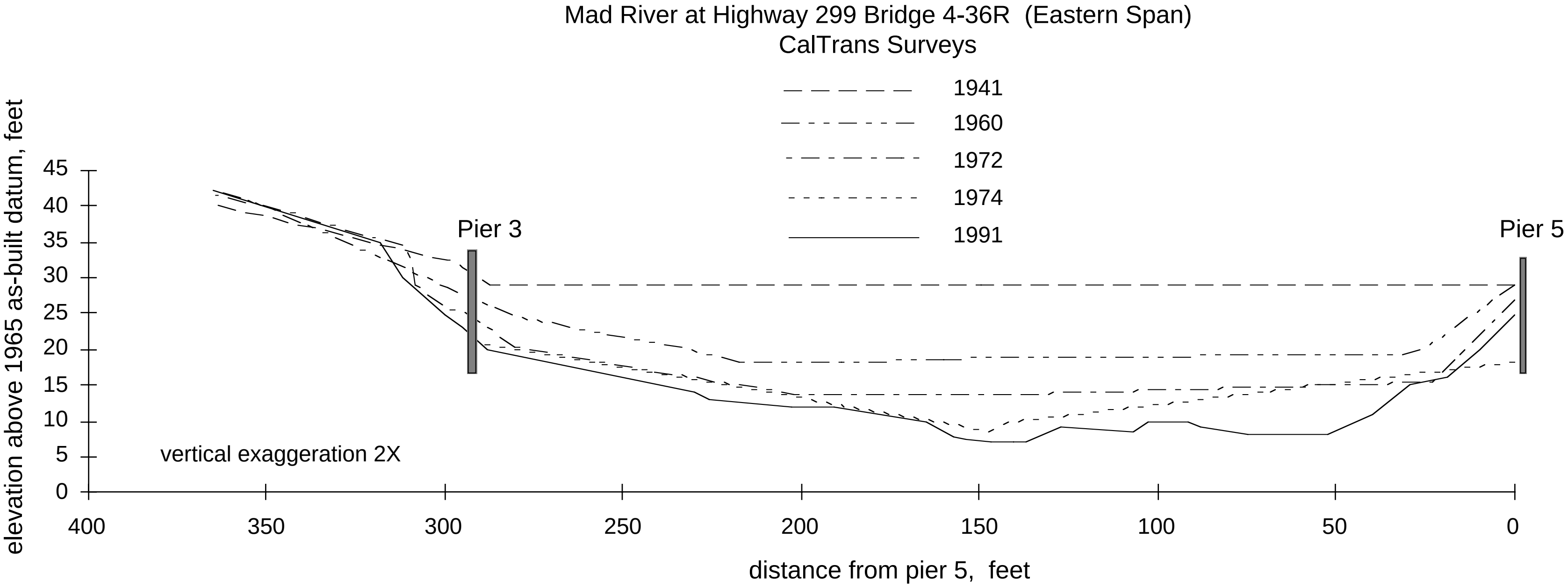


Fig. 3.A2 -- Cross-sections of the Mad River at Highway 299 bridge

View is downstream.

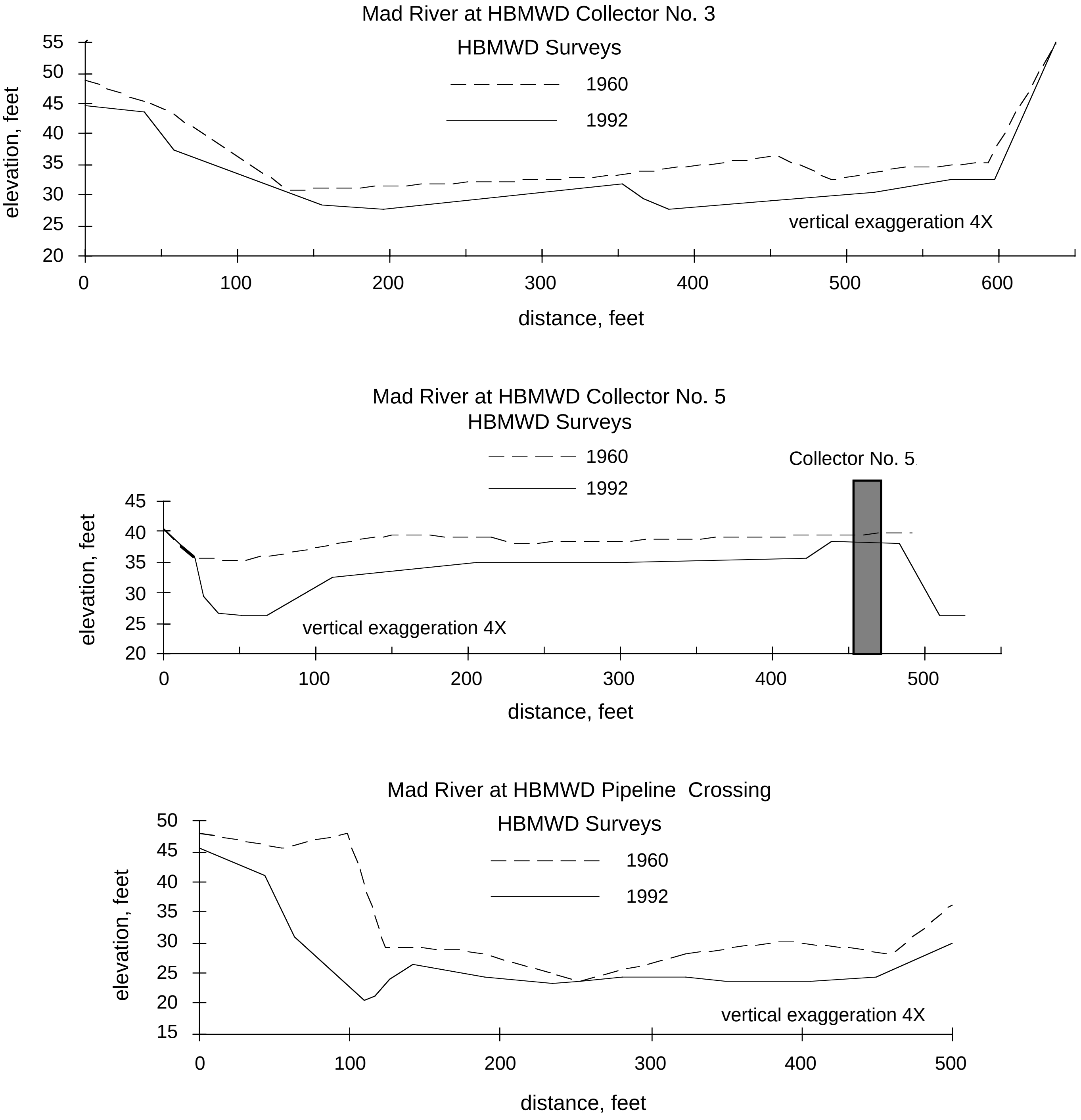


Fig. 3.A3 -- Cross-sections of the Mad River in the HBMWD reach

View is downstream.

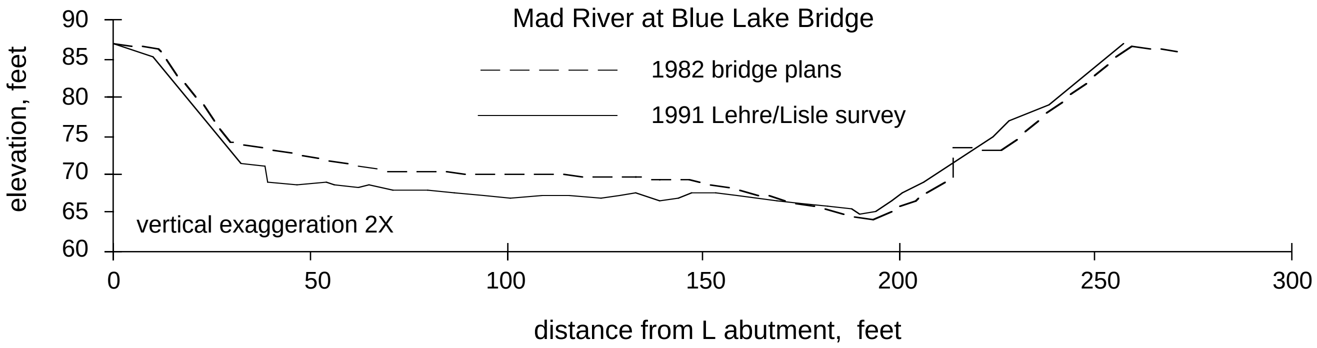


Fig. 3.A4 -- Cross-sections of the Mad River at Blue Lake (Hatchery Road) Bridge

View is downstream.

Mad River EIR Technical Supplement

Section V. Fisheries Inventory and Analysis

INTRODUCTION

Our investigation of the Mad River fishery centered on the lower mainstem channel from Mad River Hatchery to the Mad River estuary. We will not evaluate potential effects of the Blue Lake Hatchery, sport and commercial fishing, or timber harvest practices on the fishery. Rather, we present: (1) a list of species sampled in the basin, (2) a review of rearing and spawning timing for anadromous species, (3) description of rearing and spawning habitat requirements, use, and availabilty in the lower mainstem Mad River, then (4) focus on fishery concerns for the project reach concerning gravel extraction.

The following fish species have been found in the Mad River Basin, including the estuary (CDFG 1968):

Common Species

Chinook salmon	*Oncorhynchus tshawytscha*
Coho salmon	*O. kisutch*
Steelhead	*O. mykiss*
Rainbow trout (resident)	*O. mykiss*
Coastal cutthroat trout	*O. clarki*
Three-spine stickleback	*Gasterosteus aculeatus*
Riffle sculpin	*Cottus gulosus*
Coastrange sculpin	*Cottus aleuticus*
Staghorn sculpin	*Leptocottus armatus*
Shiner surfperch	*Cymatogaster aggregata*
Sacramento sucker	*Catostomus occidentalis*
Eulachon	*Thaleichthys pacificus*
Pacific lamprey	*Entosphenus tridentatus*

Infrequent Species

Sturgeon	*Alosa sapidissima*
Pink salmon	*Oncorhynchus gorbuscha*
Chum salmon	*O. keta*

Species of Unknown Status

Catfish	(sp?) Introduced in 1881.
Japanese ayu	*Plecoglossus altivelis* Introduced to Ruth Reservoir in 1964.

Presently, five anadromous salmonid spawning runs occur in the Mad River drainage: fall chinook salmon, coho salmon, winter steelhead trout, summer steelhead trout, and coastal cutthroat trout. Other anadromous salmonid species are infrequently observed. For example, in 1952, Elton Bailey, in a letter to Dick Hallock (October 23, 1952), noted "Incidentally, we took a male pink salmon in one of our seine hauls. It was in good shape and with free flowing milt."

The numerically dominant fish species in the lower mainstem (observed during everal dives in 1992) are juvenile steelhead and three-spine sticklebacks. The broad, sandy runs common in the study reach provide excellent foraging habitat for the sticklebacks.

GENERAL REARING AND SPAWNING TIMING IN THE MAD RIVER BASIN

Chinook Salmon

The chinook salmon of the Mad River exhibit the "ocean-type" behavior defined by Healey (1991) as those populations that "migrate to sea during their first year of life, normally within three months after emergence from the spawning gravel, spend most of their ocean life in coastal waters, and return to their natal river in the fall, a few days or weeks before spawning."

Adult chinook enter the Mad River with the first "substantial" fall rains in October or November (Pelgen and Fisk 1958). Historically, the first high flow event would breach the sand bar that often closed the mouth during summer low flow periods. In years when the mouth remained open, chinook entered the river as early as August, but upstream migration was often blocked by dry or extremely shallow sections a few miles from the mouth (Pelgen and Fisk 1958). Based on adult trapping data from the Mad River Hatchery, the run may extend from late August through mid February, but more typically from late-October through mid-January. Counts at the Sweasey Dam fish ladder from 1949 through 1963 indicate the peak migration usually occurs in November (approximately 75 percent), with around 15 percent in October, 10 percent in December, and less than 1 percent in January and February (CDFG 1968). Bailey (1952) reports most upstream migration occurs during the day.

Information on the timing of Mad River chinook spawning is lacking. CDFG redd counts indicate most spawning occurs in December, though poor visibility in the Mad River during the fall and winter greatly hampers direct observation. A December peak concurs with Healey's observation (1991) that chinook populations in the southern portion of their range spawn from November to January. Data on redd construction in the Mad River were not found, though chinook salmon are known to construct larger redds than other Pacific salmon species. Healey (1991) reports a range in redd surface area from 0.5 to 44.8 m^2.

The largest documented Mad River chinook salmon captured weighed 73 pounds in 1895 (Ridenhour, Johnson, and Skeesick 1961). Fish greater than 50 pounds were common until approximately 1925, when fishermen noticed declines in salmon numbers and size (Ridenhour, Johnson, and Skeesick 1961). The commercial catch in the early 1900's averaged 3 to 4 chinook salmon for every coho salmon.

The fecundity, incubation and emergence of naturally reproducing chinook salmon in the Mad River are poorly understood. Bailey (1952) calculated average fecundities of 4,421 and 4,750 eggs for chinook taken at the Sweasey Dam fish ladder in the 1950-51 and 1951-52 spawning seasons respectively. Average fecundities also are available from Mad River Hatchery reports. Barngrover (1990) estimated an average chinook salmon fecundity 3,813 eggs/female in 1988-1989 at the Mad River Hatchery. Chinook fecundity generally increases with fish size, though not to the degree reported for other species (Healey 1991). Chinook eggs spawned in the fall usually hatch by March or April, with alevins remaining in the gravel two to three weeks thereafter (Moyle 1976). Naturally spawned chinook in the Mad River probably emerge from the gravel in late-February through early-May.

CDFG downstream migrant trapping records indicate downstream smolt and pre-smolt migration begins in April, peaks in early to mid-June, and tapers to completion in late-July (Bailey 1952; CDFG 1968). Bailey (1952) also noted most downstream migration in the Mad River occurs at night, typical for the species (also Healey 1991). In his study of estuarine residence and out-migration of juvenile chinook in the Mad River, Taniguchi (1970) reported smolts first entered the estuary in early April leading to a peak in early June with peak outmigration from the estuary occuring in early July. Taniguchi (1970) also noted although the size of smolts entering the estuary in 1952 and 1969 differed significantly, the sizes on out-migration from the estuary were comparable, indicating a possible "optimum size for sea water adaptation." No studies have addressed salmonid habitat preferences in the Mad River estuary.

Coho Salmon

Adult coho may enter the Mad River as early as October but do not run in large numbers until stream flows have increased substantially (CDFG 1968). Based on adult trapping data from Mad River Hatchery, the run may extend from late-September through mid-February, but more typically from late-October through mid-January. Counts at the Sweasey Dam fish ladder from the late 1940's to the early 1960's indicate that coho stocks native to the Mad River may exhibit substantially different monthly migration patterns than the introduced Klaskanine and Quilcene strains (CDFG 1968). Most native coho migrate upstream in December, while introduced stocks peak in October (CDFG 1968). Shapovalov and Taft (1954) noted 81 percent of the total coho run passing over Sweasey Dam from 1941 through 1953 occurred in six weeks between November 12 and December 23. Most upstream coho migration takes place during the day (Sandercock 1991).

Downstream smolt migration, after rearing in the tributaries for one year and several months, peaks from mid-May through June and extends into July (Boydstun 1974).

Steelhead Trout

Steelhead trout exhibit more variable life history strategies, relative to chinook and coho salmon. Most Northern California steelhead juveniles spend one or two years in freshwater before migrating to the ocean, but three and four year freshwater residencies are found (Meehan, 1991; Trush, unpubl. data). Boydstun (1974) presents an adult scale analysis documenting a similar life history pattern for Mad River steelhead. Often, yearling and older juveniles will gradually migrate downstream. Unfortunately, most research on steelhead life history has been confined to the tributaries. Boydstun (1974) inventoried 89 miles of suitable steelhead spawning habitat in the basin's tributaries (i.e., available rearing miles). Though processes can be identified (e.g., juveniles grow as they slowly migrate downstream), the quantitative significance of each process for a basin's fish population is difficult to determine. In this example, how many two-year old juvenile steelhead depend on the mainstem channel for additional growth, compared to the number of two-year old juveniles rearing in the tributaries, then quickly migrate to the Pacific Ocean? This cannot be answered for the most studied large river in California.

Boydstun (1974) reported earlier downstream trapping at Sweasey Dam by CDFG documented most age classes were migrating from May 1 through August 1 (the sampling period), peaking in July.

Adult winter steelhead can enter the Mad River at the same time as chinook salmon (late-August), though most of the run enters later in the winter. For example, Bailey (1953) seined 252 chinook salmon and four steelhead in the Bugenig and Carson holes from October 10 to November 1952. Peak migration usually occurs from December to late February, overlapping the coho runs more than chinook runs. Boydstun (1974) suggests (on page 49) an early winter stock was present, but in low numbers. The Mad River also supports a half-pounder run of unknown size (Boydstun 1974). Spawning can occur from late-December to mid-April, depending on annual flows. Weekly salmon and steelhead counts for the Mad River Hatchery 1988 to 1989 demonstrate a typical spawning year and the timing relationships among species (Table V.1).

A run of summer steelhead, a stock of special concern (Moyle et al. 1989), enter the river in late-spring (Knutson 1975). These steelhead hold in the lower mainstem channel through the summer. Adults captured at Sweasey Dam in May were believed to be summer steelhead (Boydstun 1974) because they "lacked the physical characteristics of sexually mature fish."

Table V.1. Weekly adult salmon and steelhead trapping data for Mad River Salmon and Steelhead Hatchery, 1988 to 1989 (Barngrover 1990).

Week of:	Chinook Salmon		Coho Salmon		Steelhead
	Adult	Grilse	Adult	Grilse	Adult
Nov. 6	108	32	69	71	12
Nov. 13	26	24	106	153	69
Nov. 20	5	9	25	96	53
Nov. 27	2	9	15	121	41
Dec. 4	11	9	9	25	19
Dec. 11				2	1
Dec. 18			1		3
Dec. 25	2		12	56	197
Jan. 1	4		28		239
Jan. 8		8	18		151
Jan. 15				11	400
Jan. 22	1		2	7	258
Jan. 29			1	1	96
Feb. 5			1	2	161
Feb. 12					125
Feb. 19			5		64
Feb. 26					278
Mar. 5					167
Mar. 12					165
Mar. 19					30

JUVENILE ANADROMOUS SALMONID REARING HABITAT

All newly-emerged salmonid fry aggregate in shallow water at the stream margins, often associated with overhanging cover, backwaters, and eddies created by instream structure (Hartmann 1965; Healey 1991).

Egg survival in the basin may be low. Boydstun (1974) notes, "Turbidity has probably limited the Mad River salmon and steelhead sport fishery more than any other factor. Heavy silt loads of over 1000 ppm prevail during winter floods. Experimental incubation of king salmon eggs at Sweasey Dam in 1960-61 resulted in heavy losses due to siltation. It is assumed that survival of naturally spawned eggs in the river and tributaries is probably affected similarly by this problem."

As fry grow, they progressively move to deeper, swifter water where interspecies competition may become important. However, steelhead juveniles tend to occupy swifter, shallower riffles and runs , compared to coho juveniles that prefer slower flowing habitats (especially pools with abundant woody debris) (Meehan 1991). For coastal streams in British Columbia, Hartman (1965) observed both species occupy different microhabitats; coho salmon utilized pools and steelhead occupied riffles.

Annual peak downstream migration, in the river and entering the estuary, occurs at the same time, indicating Mad River juvenile chinook spend little time rearing in the lower mainstem (CDF&G[1] 1968; Taniguchi 1970). The estuary could serve as the primary rearing habitat until outmigration to the ocean. No studies to date have quantified or assessed juvenile salmonid habitat in the Mad River estuary or lower mainstem. On July 15, Don La Faunce (CDFG 1976, letter to Region 1) noted the Mad River at the Highway 299 bridge was almost dry. Over a 0.25 mile reach, from the lowermost water collector to the bridge, CDFG found 300 juvenile steelhead (2.5 to 6.0 inches long) and 300 juvenile chinook salmon (2.5 to 3.0 inches long). While these counts cannot be used for fish density estimation, the data do show juvenile salmon occupy the channel in mid-July. No juvenile coho salmon were found.

Snorkel surveys of the lower Mad River indicate large woody debris may provide critical cover in an otherwise "cover-limited" stream. On October 17, 1992, Terry Roelofs (HSU), Bill Trush (HSU), Brian Winters (CDFG), and eight Humboldt State University Fisheries students snorkeled several sections of the lower mainstem, including the reach above the railroad bridge to the Eureka Sand and Gravel Bar (below Blue Lake Bridge). The purpose of the survey was to estimate abundances of rearing juveniles and adult spawners. Few juveniles were observed. Four yearling steelhead were seen under the bridge abutment of the railroad bridge. Four young-of-the-year steelhead were counted in the eddy of a six foot boulder, approximately 300 feet upstream of the railroad bridge. No other salmonids were observed (sticklebacks and suckers were abundant). Divers noted juvenile steelhead were usually associated with large woody debris. Woody debris and undercut banks (uncommon in lower mainstem) are critical over-wintering habitat for both species (Hartman 1965).

UPSTREAM MIGRATION AND SPAWNING HABITAT

Chinook salmon, coho salmon, steelhead trout, and cutthroat trout spawn in tributaries and the mainstem of the Mad River Basin. All anadromous species are prevented from utilizing the entire basin by natural barriers. On the mainstem, a twenty five foot waterfall approximately

24 miles above the Sweasey Dam site, roughly 0.5 miles below the Bug Creek confluence, stops upstream migration (CDWR 1958). A steep cascade five miles upstream from the mouth of the North Fork Mad River also prevents salmon migration and greatly restricts steelhead access. Removal of both barriers would approximately double basinwide anadromous fish spawning habitat at the time of this assessment (CDWR 1958).

Principal spawning tributaries downstream of the Mad River Hatchery are the North Fork Mad River, Lindsay Creek, Mill Creek, and Warren Creek (Plate 2). Lindsay Creek, the largest tributary downstream of the North Fork, has approximately 7 miles of spawning habitat (McCormick 1956). Lindsay Creek has the dual distinction of being been cited as "Lindsey has the reputation of being the best local stream for cutthroat trout fishing" (McCormick 1956) and "Lindsay Creek is the most important silver salmon tributary in the Mad River drainage" (CDFG Water Projects Branch 1968). McCormick (1956) estimated 200 to 250 coho salmon, 50 chinook salmon, a few steelhead trout, and an unknown number of cutthroat trout spawn annually in the creek. A USFWS investigation (1967), responding to a proposed dam on Linsay Creek by the Army Corps of Engineers, estimated 1000 coho salmon, 800 chinook salmon, and 800 steelhead trout annually spawned.

The best record of upstream adult migrants is the Sweasey Dam fish ladder counts from 1938 to 1964 (Table V.2). Boydstun (1974) notes the Sweasey Dam counts represent approximately ten percent of the annual spawning run. While chinook salmon, coho salmon, and steelhead trout exhibit decreasing numbers over the counting period, the variation between successive years is considerable (e.g., the coho salmon count in 1962). Migration blockage by the ladders probably underestimate run size at the dam (Ridenhour, Johnson and Skeesick 1961). Annual anadromous fish runs to the Mad River Hatchery have been extremely variable (Barngrover 1990) during operation of the hatchery from 1971 to the present (Table V.3). Operation of the fish weir and various stocking efforts (e.g., a 1957 coho salmon stocking program) also affected continuity of the record, .

Few annual salmon run estimates are available below the Sweasey Dam site. Ridenhour, Johnson, and Skeesick (1961) estimated an annual chinook salmon run of 10,000 fish in 1905 using cannery records. In the early 1950s, CDFG attempted to quantify the total annual chinook spawning run. Bailey (1953) estimated, from their mark-recapture results, 6,320 adult chinook entered the river in the 1952 spawning run. Tagging was accomplished by seining and tagging 252 fish from three pools in the tidal zone. Recovery of tagged salmon were from three sources: carcass recoveries, Sweasey Dam fish ladder counts, and angler catch. Gibbs (1955) estimated 3900 chinook salmon entered the river in 1954 using similar methodologies (however, only 82 chinook were tagged in the mark-recapture experiment). Given the large error in mark-recapture methodologies, both annual chinook population estimates must be considered extremely conservative.

Salmon and steelhead do spawn in the study reach. During the 1977 drought year, forty redds were observed by CDFG from Mad River Hatchery downstream to the 101 Highway Bridge (Temple and Hansen 1977). "Most" redds were sighted above the railroad bridge. A CDFG (1992) redd survey documented eight steelhead redds from Mad River Hatchery to Blue Lake Bridge.

Only limited data are available on direct consequences of changing channel morphology on adult anadromous fish holding habitat and upstream access within the study site. We were unable to inventory potential spawning sites in January through March of 1993 because of high flows and extreme water turbidity. A CDFG report (1956), on riffle dimensions from the

Essex Diversion to the Pifferini Riffle, documented one riffle in a gravel operation (below the 299 Bridge 605 feet long and 80 feet wide at 22.8 cfs on August 23, 1956. The greatest water depth across a transect through the riffle was 0.2 feet. Another riffle at an unspecified gravel operation was 43 feet long but 140 feet wide with a maximum water depth of 0.2 feet. Water depths at this low flow (22.8 cfs) may not be a barrier because migration would not have commenced (an average velocity of 1.4 fps). A 100 cfs flow, a potential spawning flow early in the fall, would average 0.63 feet deep at the first site (assuming velocity of 2.0 fps and no change in width), below the minimum migration depth of 0.80 feet (McLeod 1987).

Table V.2. Sweasey Dam anadromous fish counts (CDFG 1968).

Year	Chinook	Coho	Steelhead
1938	1273	498	3110
1939	1257	725	3118
1940	1293	73	5706
1941	3139	308	4583
1942	1676	378	6650
1943	1236	259	4921
1946	1181	415	5106
1947	717	510	3582
1948	672	515	3139
1949	484	512	4074
1950	1505	147	4430
1951	1519	414	5543
1952	401	72	5613
1953	847	91	2943
1954	409	59	2390
1955	390	2	148
1956	129	21	2717
1957	494	11	1957
1958	478	3	1780
1959	19	541	1376
1960	55	244	1343
1961	40	710	1985
1962	238	3580	1708
1963	232	1419	2178
1964	492	332	373

Table V.3. Summary of salmon and steelhead runs to Mad River Salmon and Steelhead Hatchery (Barngrover 1990).

Year	Chinook		Coho		Steelhead
	Adults	Grilse	Adults	Grilse	
1971-1972	238	85	268	69	42
1972-1973	656	380	235	231	52
1973-1974	390	105	281	46	1086
1974-1975	181	50	141	19	311
1975-1976	94	184	506	1597	190
1976-1977	478	661	217	976	658
1977-1978	163	87	452	194	1191
1978-1979	56	190	73	524	2190
1979-1980	128	17	129	223	1411
1980-1981	66	20	162	341	730
1981-1982	38	213	78	135	442
1982-1983	648	900	149	473	1087
1983-1984	313	124	22	65	774
1984-1985	34	48	20	4	585
1985-1986	177	98	38	7	753
1986-1987	227	72	59	265	13807
1987-1988	568	278	220	733	4303
1988-1989	159	83	254	591	2529

SPECIFIC FISHERIES MANAGEMENT CONSIDERATIONS

Specific potential concerns for adult holding habitat and mainstem access within the study reach include:

(1) possible warming temperatures below the Humboldt Water District intakes may inhibit farther upstream migration during low autumn flows.

(2) loss of channel structure (fewer shallower pools and overall decreased amounts of inchannel woody debris) provides poor holding cover.

-The Mill Creek Hole in Elton Bailey's 1953 spawner report was a well known hoding area of upstream spawners. Lowering of the main channel may have affected this hole.

-Dives by Terry Roelofs, Bill Trush, and fisheries students in summer 1992 found holding summer steelhead were associated with woody debris accumulations in fast moving runs and riffles, all unmined channel reaches.

(3) artificially produced pools may concentrate fish in upstream ends (fish utilizing bubble curtain as only cover), increasing vulnerability to poaching and excessive fishing pressure.

-Interviews with local anglers indicate upstream ends of long trenches are "hot spots" for catching salmon and steelhead.

(4) scraped riffles may become too broad to support minimum water access depths during early autumn upstream migration under relatively (compared to typical November flows) low flows.

-Spawner access to the basin has always been a partial function of flow. Low flows in October and/or November often confined adults to the lower channel until sufficient rainfall improved access. For example, in 1952 the mouth remained open through the summer and fall, allowing chinook salmon to enter the river by August 28 (Bailey 1953). However, river flow did not permit upstream migrants to ascend higher than the North Fork confluence; several river reaches were completely dry until November 14.

Specific potential concerns for spawning habitat within the study reach are:

(1) downcutting of the mainstem could propagate into the tributaries, decreasing or eliminating access by upstream migrating adult salmonids.

-Field inspection of Warren, Lindsay, and Mill Creek confluences found clear evidence of channel downcutting (see Channel Bed and Bank Erosion section). However access does not appear impaired at Warren and Lindsay Creeks. The steep, constructed boulder cascade at the mouth of Mill Creek could be a partial barrier.

(2) alteration of the planform and hydraulic geometry could reduce spawning habitat quality by creating unfavorable water depths and velocities over former spawning beds, and by altering the bed composition of the spawning beds.

-Because of the high flows and extreme turbidity in January through March of 1993, we could not inventory and/or qualify contemporary spawning habitat. Qualitative surveys by Trush in 1991 found many pool tails, on mined and unmined reaches, had sufficient depths and a proper range of velocities for supporting favorable spawning environment. No data are available characterizing gravel bed composition, or assessing changes to gravel composiiton directly attributable to gravel extraction.

(3) channel alterations reduce habitat quantity below the Mad River Hatchery.

-Review of aerial photos indicate (see other sections of this report) a reduction in riffles and an increase in runs. However, aerial photo scale does not permit a more intensive assessment.

(4) greater fishing pressure increases disturbance of spawning fish and increase poaching (when the fish are extremely vulnerable), especially with lack of cover.

Specific potential concerns for rearing habitat and downstream smolt migration in the study are:

(1) loss of riffles (converted to deep runs and trenches) reduces rearing habitat for juvenile steelhead trout and benthic invertebrate production.

(2) lack of woody debris in mined riffles and pools also reduces habitat quality for all rearing salmonid species.

-Lack of habitat structure probably is the major impact of gravel extraction. Without sampling fish densities in channel reaches with and without woody debris, the biological effect of an absence of woody debris was not estimated.

-The right bank channel below Eureka Sand and Gravel but above recent mining (just upstream of the A&MRR bridge) retains the most woody debris in the study reach. This unconfined reach has not been mined for many years, and would function as an excellent future monitoring site.

(3) downstream migration of chinook fry can extend into July. Care should be taken to avoid trapping fish in irrigation inlets and trenching; production of suspended sediment during trenching probably is not physiologically harmful to juveniles, but may force individuals from cover and/or displace others downstream.

(4) invertebrate adundance was not quantitatively assessed due to lack of data. Short (less than 100 feet), steep riffles produced sufficient bed surface coarsening (large gravel and cobbles) to support diverse and dense invertebrate populations (Trush, personal observation). These riffles were unmined.

(5) downstream migrant trapping documents peak salmon migrations during the extraction season, June through July. Juvenile steelhead migrate downstream throughout the summer.

(6) warm summer water temperatures in the lower mainstem (Boydstun 1974; Barngrover 1990) may require juveniles to seek cool water. Stream confluences and intergravel flow at the downstream base of gravel bars should be identified, mapped, and maintained as juvenile rearing habitat

SUMMARY

Lack of rearing and spawning data for the lower mainstem precludes a satisfactory evaluation of potential gravel extraction effects on fisheries. In lieu of badly needed habitat inventories and fish monitoring, the following concerns can be highlighted:

(1) Juvenile salmonids are actively migrating through the lower mainstem during the spring and most of the summer. Screening of water intakes and potential juvenile fish isolating depressions/trenches, especially during declining spring flows, should be closely monitored.

(2) Lack of woody debris probably limits juvenile rearing habitat and adult salmonid holding habitat, particularly for summer steelhead. Woody debris, particularly large trees, should be left intact on the bars (to be re-worked into the wetted channel by the next flood) and inchannel. Sections of the river should be maintained as "free zones" were mining is restricted, to allow woody debris accumulation and development of steep, coarse riffles for invertebrate production and juvenile steelhead rearing habitat.

(3) Trenching may concentrate adult fish at the entrance, increasing vulnerability to poaching and excessive angling pressure. Besides the serious problem of routing sediment through mainstem trenching, trenches probably should be avoided for fisheries concerns: marginal adult holding habitat and unsatisfactory rearing habitat.

(4) Cold water pockets in the lower mainstem should be identified, mapped, and maintained as fish rearing habitat.

(5) Post-extraction channel geometries, at summer's end, should have a minimum depth of one foot at typical August and September low flows. High winter flows may reshape the channel geometry, but this provision would allow free migration upstream during a low flow autumn. A "design" low flow should be established by CDFG for consideration in the annual 1603 gravel extraction agreements.

FISHERIES REFERENCES

ANONYMOUS. 1956. Mad River riffle measurement from Essex Diversion to Pifferini Riffle. CDFG File.

ANONYMOUS. 1991. Summer steelhead, spring run chinook surveys 1991. USFS/CDFG file, Eureka.

BAILEY, ELTON D. 1952. A first progress report on the experimental program for the Mad River, Humboldt County, California. CDFG Report. 29 pages.

BAILEY, ELTON D. 1952. Letter to Dick Hallock regarding Mad River fish tagging. CDFG File, Eureka.

BAILEY, ELTON D. 1953. CDFG memorandum - Mad River, Humboldt County king salmon spawning run, 1952. CDFG File, Eureka.

Bailey, Elton D. and Earl D. Gibbs. 1963. Observations of the seaward migrations of hatchery reared and wild juvenile king salmon. CDFG, Marine Resources Admin. Rept. No. 64-5, 13 pp.

BARNGROVER, BRUCE G. 1990. Annual report: Mad River Salmon and Steelhead Hatchery, 1988-89. Inland Fisheries Administrative Report No. 90-14. 14 pages.

BOYDSTUN, L. B. 1974. The Mad River 1973-74 salmon and steelhead fishery, with recommendations regarding management of the river's salmon and steelhead resources. CDFG File, Eureka.

CDFG. 1968. An evaluation of the fish and wildlife resources of the Mad River as affected by the U.S. Corps of Engineers Mad River Project with special reference to the proposed Butler Valley Reservoir, CDFG File, Eureka.

CDFG. 1968. Reconnaissance fish and wildlife evaluation of possible water projects on Lindsay Creek and M-Line Creek, Humboldt County. Office Report, Eureka.

CHUPP, NORMAN R. 1967. USFWS letter to Corps. of Engineers regarding proposed dam construction on Maple Creek, Little River and Lindsay Creek. CDFG File, Eureka.

GIBBS, EARL. 1955. Letter to Elton Bailey - Mad River king salmon run -1954. CDFG File, Eureka.

FROLAND, JIM AND JOANN FROLAND. 1992. Mad River redd/salmon survey field notes for 11/23/92. CDFG File, Eureka.

HANSEN, TED M. AND E. R. TEMPLE. 1977. CDFG memorandum regarding swimming survey of Mad River downstream from the hatchery - September 22, 26 and 27, 1977. CDFG File, Eureka.

HARTMAN, G. F. 1965. The role of behavior in the ecology and interaction of underyearling coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). J. Fish. Res. Bd. Can., 22(4): 1035-1081.

HEALEY, M. C. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*) *in* Pacific Salmon. Ed. Groot, C. and L. Margolis. UBC Press. 564 pages.

KNUTSON, A. C., JR. 1975. Biology of summer steelhead (*Salmo gairdnerii gairdnerii*), in Mad River, California. M.S. Thesis, Humboldt State University.

LA FAUNCE, DON A. 1976. CDFG memorandum: Reduced flows in Mad River. CDFG File, Eureka.

LEE, DENNIS P. 1975. Note on Mad River near the end of the Warren Creek Road. CDFG File, Eureka.

McCORMICK, RALPH B. 1956. Value of Lindsay Creek for salmonid spawning letter to Chet Woodhull. CDFG File, Eureka.

McLEOD, DAVID A. 1980. Field note - spring run steelhead inventory from E & O Hole to Pifferini Hole. CDFG File, Eureka.

McLEOD, DAVID A. 1982. Recreational angling use and catch in the Mad River, July 1981 - June 1982. CDFG File, Eureka.

McLEOD, DAVID A. 1987. CDF&G memo: Preliminary critical riffle data for Mad River and Redwood Creek. CDFG File, Eureka.

McLEOD, DAVID A. 1988. Note to Phil Baker - Critical riffle study on Redwood Creek and Mad River. CDFG File, Eureka.

McLEOD, D. A., AND L. PRESTON. 1992. Mad River salmon spawning survey field notes for 11/18/92. CDFG File, Eureka.

MEEHAN, W.R. (ed.) 1991. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication No. 19, 751 pp.

MOYLE, P. B., J. E. WILLIAMS AND E. D. WIKRAMANAYAKE. 1989. Fish species of special concern of California. Rept. to CDFG. Contract No. 7337. 222 pages.

MOYLE, P. B. 1976. Inland fishes of California. UC Press. 405 pages.

PELGEN, DAVID E., L. O. FISK AND J. C. FRASER. 1958. Office report on preliminary investigation of Mad River - A preliminary evaluation of the effect of the Ruth Dam Project on fisheries of the Mad River. State of California Dept. of Water Resources, Division of Resources Planning. CDFG Report.

RIDENHOUR, RICHARD L., A. K. JOHNSON AND D. G. SKEESICK. 1961. Survey of the Mad River with special reference to king salmon. CDFG and Humboldt State College. 44 pages.

SANDERCOCK, F. K. 1991. Life history of coho salmon (*Oncorhynchus kisutch*) *in* Pacific Salmon. Ed. Groot, C. and L. Margolis. UBC Press. 564 pages.

SHAPOVALOV, L. AND A. C. TAFT. 1954. The life histories of steelhead rainbow trout (*Salmo gairdneri gairdneri*) and silver salmon (*Oncorhynchus kisutch*) with special reference to Waddell Creek, California, and recommendations regarding their management. Fish Bulletin No. 98. CDFG. 379 pages.

SIMPSON D. A. AND HELEN SIMPSON. Notes on fish species collected September 22 and 23, 1945 near U.S. 101 bridge, near Highway 299 bridge and 2 miles southeast of Blue Lake. CDFG File, Eureka.

TANIGUCHI, A. K. 1970. Interval of estuarine residence and out-migration of the juvenile chinook salmon in the Mad River, California. M.S. Thesis, Humboldt State University.

U.S. ARMY CORPS OF ENGINEERS. 1968. Interim review report for water resource development on the Mad River.

U.S. ARMY CORPS OF ENGINEERS. 1973. Draft EIR - Butler Valley Dam and Blue Lake Project.

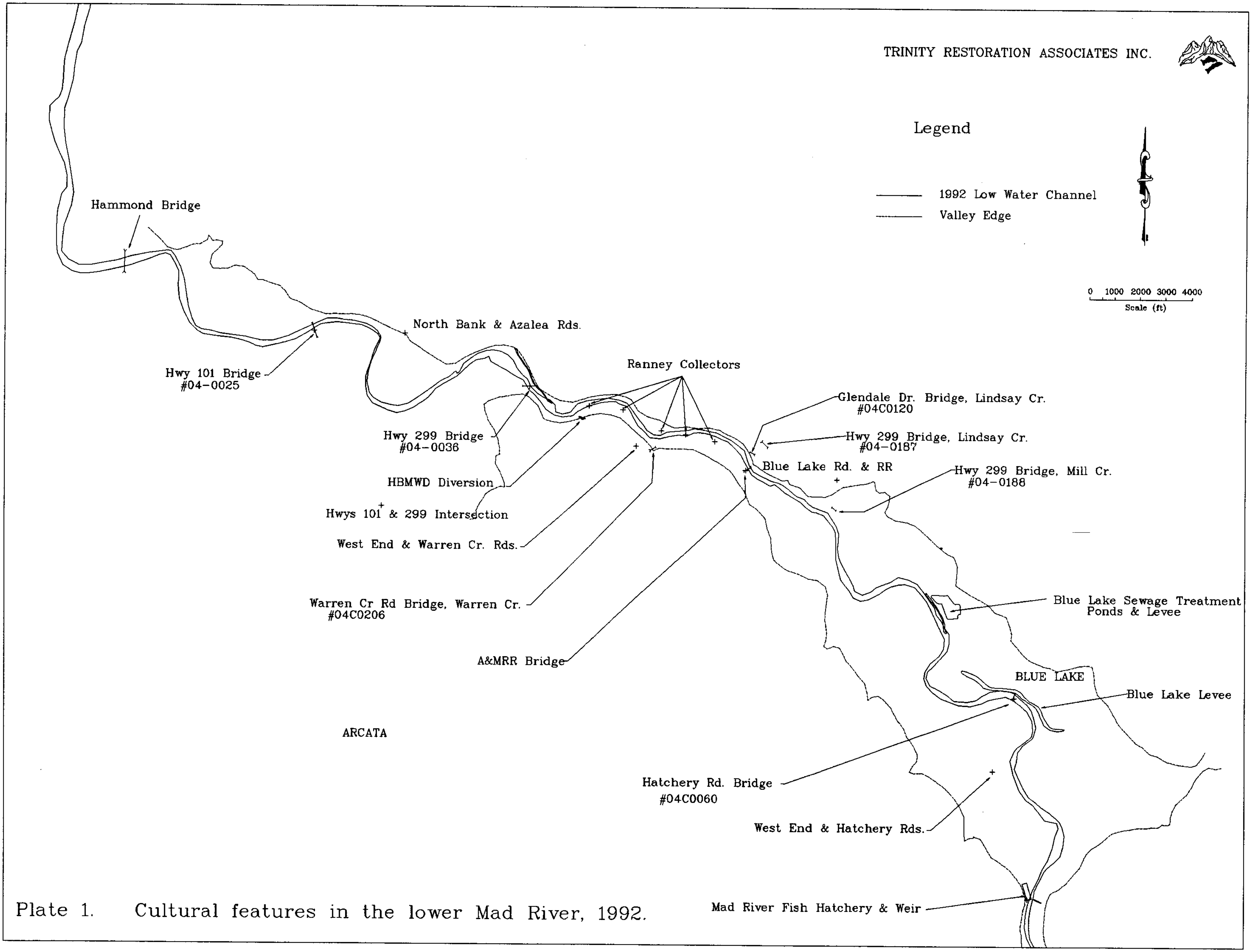


Plate 1. Cultural features in the lower Mad River, 1992.

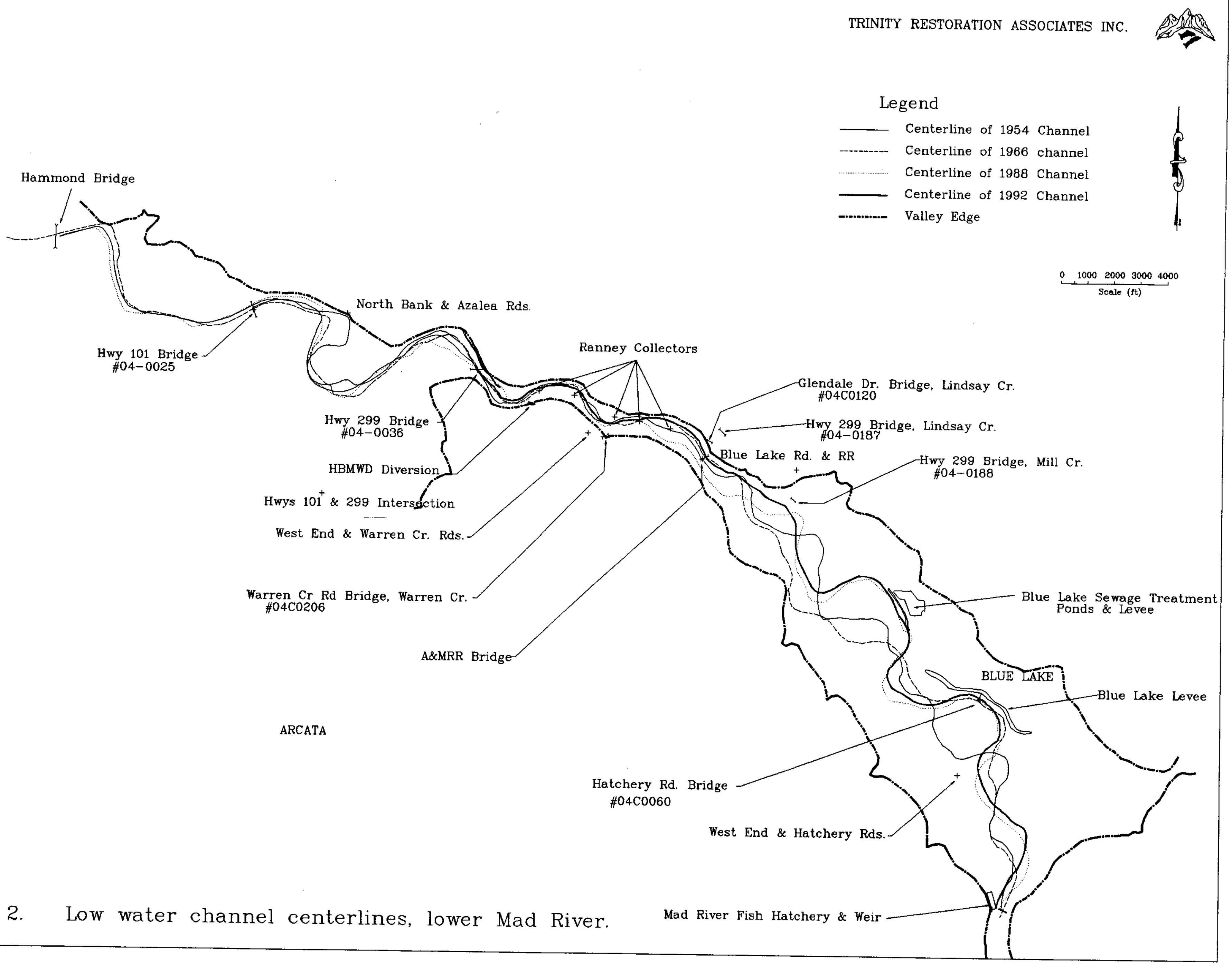


Plate 2. Low water channel centerlines, lower Mad River.

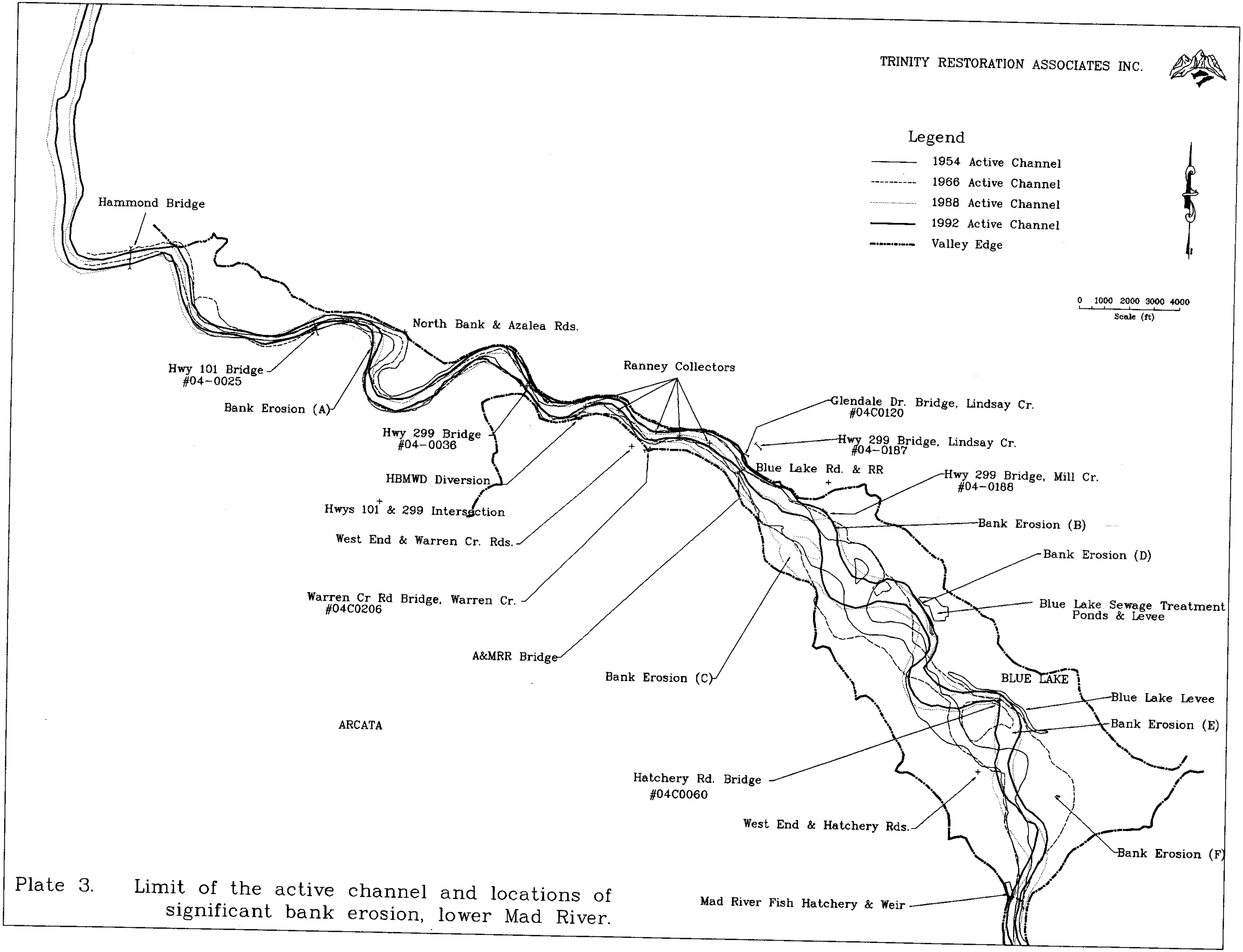


Plate 3. Limit of the active channel and locations of significant bank erosion, lower Mad River.