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Technical Report: TR-TRRP-2011-2

2010 Bed-material Sediment Budget Update, Trinity River, Lewiston Dam to Douglas City, California

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U.S. Department of the Interior
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Purpose and Scope

This report incorporates water year (WY) 2010 sediment transport measurements and 2010 coarse sediment additions to update and refine previously-prepared sediment budgets evaluating changes in bed material storage in the Trinity River downstream from Lewiston Dam (GMA 2001; Wilcock 2004; Gaeuman 2008; Wilcock 2010). These sediment budgets are crucial for guiding numerous management activities, including flow release scheduling, coarse sediment augmentation, tributary sediment control, and mechanical channel rehabilitation strategies.

Bed material sediment in the Trinity River is usually classified into two size fractions: fine bed material, defined as particles between 0.5 and 8 mm (about 1/50 to 5/16 in.) in diameter, and coarse sediment, which is defined by particles larger than 8 mm in diameter (TRFES 1999). Separate budgets are developed for each size fraction. Particles smaller than 0.5 mm in diameter comprise a very small fraction of the stream bed, and so are not generally considered “bed material” in the Trinity River system (Wilcock et al. 1996a).

Assessment of changes in coarse sediment storage is key for managing the coarse sediment augmentation program implemented by the Trinity River Restoration Program (TRRP). All coarse sediment from the upper basin is trapped in the reservoirs behind Trinity and Lewiston Dams. In the absence of sediment augmentation, any coarse sediment transport downstream from Lewiston Dam adds to an ever-growing deficit in the quantity of mobile coarse bed material that is available for subsequent transport. The deficit is most pronounced in the immediate vicinity of the dam and gradually diminishes with distance downstream as cumulative tributary contributions and sediment fluxes from upstream increase (Williams and Wolman 1984). Such cumulative losses in gravel storage have the potential to degrade salmonid habitat by coarsening the channel bed, decreasing bed mobility, and reducing in-channel topographic relief.

At its core, coarse sediment augmentation in the Trinity River has one physical purpose. That is, to ensure that the quantity of mobile coarse bed material available for transport in the river is sufficient to support bar formation and a continual reshaping of channel topography. This end is embodied in two sub-objectives: a short-term sub-objective to increase storage of gravel and small cobble bed material in the upper river to pre-dam levels, and a long-term sub-objective to maintain that storage level by continuously replenishing the coarse sediment that is transported downstream by environmental flow releases (TRFES 1999). A coarse sediment budget is necessary to evaluate progress toward both.

Reducing the quantity of fine bed material stored in the reaches downstream from Lewiston Dam is another primary management objective of the TRRP. Although Trinity and Lewiston Dams trap virtually all of the bed material generated in the upper basin, the quantity of sediment delivered from downstream tributaries was unaffected by dam construction. High fine sediment loads from some tributary areas combined with regulated streamflow in the first few decades after dam closure allowed fine bed material to accumulate in downstream reaches, where it can bury the gravel substrate needed for food production and salmonid spawning, fill pools used by adult fish, and contribute to channel narrowing and habitat simplification (Wilcock et al. 1996a). Consequently, flow release hydrographs specified in the Trinity River Record of Decision (ROD 2000) are designed, in part, to annually flush as much or more fine bed material from the Trinity River as is delivered by tributaries between Lewiston Dam and the North Fork Trinity River. In addition to these flushing flows, TRRP management activities include a watershed rehabilitation component specifically intended to reduce tributary fine sediment production and the delivery of fine sediment to the mainstem Trinity River. A fine bed material budget is required to determine whether these management activities are effective.

Methods and Data Sources

A sediment budget tracks changes in sediment storage (ΔS_{ij}) in a particular area, *i*, over a particular time period, *j*, according to:

$$\Delta S_{ij} = I_{ij} + E_{ij}$$

Where I_{ij} is the total amount of sediment that enters area *i* in time period *j*, and E_{ij} is the total amount of sediment exported from the same area in the same time period. Sediment budgets for the Trinity River make use of four budget areas, hereafter referred to as budget cells, whose boundaries are defined by four sediment monitoring locations and Lewiston Dam, which serves as the upstream boundary for the entire study area. From upstream to downstream, the four monitoring locations are referred to as Trinity River at Lewiston (TRAL), Trinity River above Grass Valley Creek (TRGVC), Trinity River at Limekiln Gulch (TRLG), and Trinity River at Douglas City (TRDC). Budget cells defined by these boundaries are Lewiston Dam to TRAL (budget cell 1), TRAL to TRGVC (budget cell 2), TRGVC to TRLG (budget cell 3), and TRLG to TRDC (budget cell 4). Locations of sediment monitoring stations, budget cells, and major tributaries are illustrated in Figure 1.

The input and export terms are composed of a variety of sediment sources or sinks. In the case of the Trinity River budgets developed below, inputs to each budget cell includes sediment transported into the cell from the budget cell immediately upstream, sediment delivered to the cell from tributary watersheds, sediment eroded from the stream banks, and coarse sediments added to the active channel as part of gravel augmentation activities. The export term for each cell is equal to the quantity of sediment transported across the downstream boundary of the cell. Wherever possible, the input and export quantities used by Wilcock (2010) for WY 2004 through 2009 are retained in the computations to follow.

Mainstem Sediment Transport Sampling and Load Estimates

The export terms for the four Trinity River budget cells are based on load computations reported by Graham Matthews and Associates, Inc (GMA). The loads are based on bedload and suspended sediment transport samples collected by GMA during high flow periods (most recently, GMA 2011). Output terms for each budget cell for WY 2004-2010 are given in Table 1.

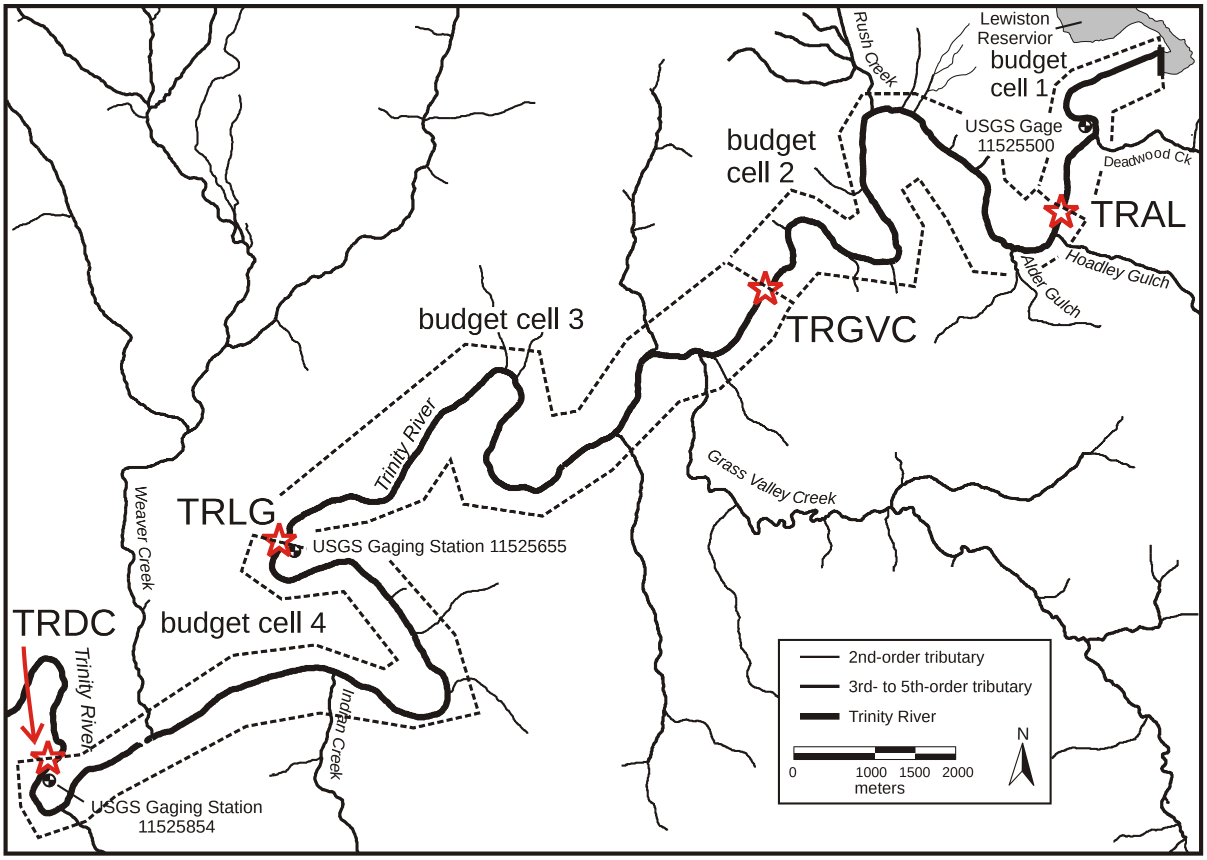

Figure 1: Map of the Trinity River basin downstream from Lewiston Dam showing the locations of sediment monitoring stations and sediment budget cells.

Some of the export terms used by Wilcock (2010) have been modified in Table 1 as follows: Terms given with the c1 subscript are as reported by GMA (2007), whereas Wilcock (2010) estimated the loads using sediment rating curves. The c2 subscript identifies corrected washload terms for which Wilcock (2010) reported the entire suspended load, including the 0.5-2 mm fraction. The c3 subscript indicates a correction to the 2006 suspended bed material load, as reported by GMA (2007). The value for suspended sand transport at the Limekiln Gulch sediment monitoring location originally reported for 2006 by GMA was unrealistically large at 111,690 tons. This is 40 times larger than the corresponding value reported for the next sampling location upstream and 3.6 times larger than the value reported for the next sampling location downstream, where the fine sediment supply is much larger. This unusually large load was computed using turbidity as a surrogate to interpolate between the collection times for actual suspended load samples (GMA 2007). However, turbidity is most sensitive to changes in the concentrations of particles fractions smaller than about 0.04 mm (Gray and Gartner 2009), and so is a questionable surrogate for the quantification of suspended sand. The suspended sand load identified with the c3 subscript in Table 1 was therefore recomputed using a sediment rating curve fit to the concentrations of suspended sand in the actual suspended sediment samples.

Table 1: 2004-2010 sediment export terms used in the updated Trinity River sediment budgets. The fine bed material term is the sum of the bedload and suspended 0.5-8 mm terms. Sediment transport was not measured at TRGVC prior to WY 2006; estimates indicated with * are those of Wilcock (2010). Subscripts are as described in the text.

	2004	2005	2006	2007	2008	2009	2010
Loads at TRAL (Export from Cell 1)	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)
Coarse Sediment (> 8 mm)	1700	531	8610	93	863	260	550
Fine Bed Material (0.5-8 mm)	353	298	1430	113	444	65	39
Bedload (0.5-8 mm)	282	235	1430	77	236	65	39
Suspended (0.5-8 mm)	71	63	0	36	208	0	0
Washload (< 0.5 mm)	483	459	2670	195	456	488	406
Loads at TRGVC (Export from Cell 2)							
Coarse Sediment (> 8 mm)	1336*	1789*	4290_{c1}	71	1750	470	492
Fine Bed Material (0.5-8 mm)	3190*	2908*	6070_{c1}	785	2082	542	377
Bedload (0.5-8 mm)	na	na	3280_{c1}	444	1260	542	377
Suspended (0.5-8 mm)	na	na	2790_{c1}	341	822	0	0
Washload (< 0.5 mm)	3805*	3495*	9490_{c1}	1270_{c2}	2250_{c2}	1574	2940
Loads at TRLG (Export from Cell 3)							
Coarse Sediment (> 8 mm)	1359	1853	4350	12	775	34	364
Fine Bed Material (0.5-8 mm)	2008	2061	10895	484	2223	293	801
Bedload (0.5-8 mm)	1649	1314	6660	278	1330	236	666
Suspended (0.5-8 mm)	359	747	4235_{c3}	206	893	57	135
Washload (< 0.5 mm)	2871	2868	45800	2200	3480	1797	3110
Loads at TRDC (Export from Cell 4)							
Coarse Sediment (> 8 mm)	4869	5229	15200	297	2380	634	1650
Fine Bed Material (0.5-8 mm)	5452	7024	43800	2393	5340	1354	2650
Bedload (0.5-8 mm)	3754	5064	12700	733	2510	882	1690
Suspended (0.5-8 mm)	1698	1960	31100	1660	2830	472	960
Washload (< 0.5 mm)	8359	9271	298000	9530	11700	4554	7460

Sediment Inputs Terms

Sediment input terms used to calculate the 2010 sediment budgets are given in Table 2.

<u>Tributary Inputs:</u>

The actual magnitudes of most of the input terms, with the exception of the coarse sediment augmentation quantities, are highly uncertain. Numerous tributaries can deliver significant quantities of bed material to the Trinity River, particularly in the finer fractions. It is logistically impractical to monitor all the relevant tributaries, or to monitor them with sufficient temporal resolution to capture the major sediment transporting events. High rates of sediment delivery can occur for relatively brief periods at the tributary mouth during or sometime after major storm events, depending when and where mass failures occur in the watershed. Consequently, the sediment delivery rates of most tributaries have never been measured, and measurements are few even in the tributaries that have been monitored.

Table 2: 2004-2010 sediment input terms used in the updated Trinity River sediment budgets. Deviations from values reported by Wilcock (2010) are explained in the text. Coarse sediment augmentation figures given here do not include material placed at channel rehabilitation sites during the 2010 fall construction season.

	2004	2005	2006	2007	2008	2009	2010
Lewiston Dam to TRAL (Cell 1)	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)
Deadwood Creek (> 8 mm)	70	1	384	1	0	0	0
Deadwood Creek (0.5-8 mm)	208	82	1609	48	14	13	41
Bank Erosion (> 8 mm)	41	41	41	41	41	41	41
Coarse Sediment Augmentation	3000	0	0	2432	9000	7300	2370
TRAL to TRGVC (Cell 2)							
Coarse Sediment from Cell 1	1700	531	8610	93	863	260	550
Fine Bed Material from Cell 1	353	298	1430	113	444	65	39
Rush Creek (> 8 mm)	175	3	960	1.4	0	0	0
Rush Creek (0.5-8 mm)	495	196	3830	50	33	31	98
Lewiston Tribs (> 8 mm)	0	0	0	0	0	0	0
Lewiston Tribs (0.5-8 mm)	256	96	665	24	27	21	60
Bank Erosion (> 8 mm)	597	597	597	597	597	597	597
Debris from Burn (0.5-8 mm)	0	0	13000	0	0	0	0
Coarse Sediment Augmentation	0	0	0	0	1000	9250	8550
TRGVC to TRLG (Cell 3)							
Coarse Sediment from Cell 2	1336	1789	4290	71	1750	470	492
Fine Bed Material from Cell 2	3190	2908	6070	785	2082	542	377
Grass Valley Creek (> 0.5 mm)	0	0	0	0	0	0	0
Trinity House Gulch (> 8 mm)	0	0	0	0	0	0	0
Trinity House Gulch (0.5-8 mm)	168	50	1198	30	8	8	25
Bank Erosion (> 8 mm)	940	940	940	940	940	940	940
Coarse Sediment Augmentation	0	0	0	0	0	0	2295
TRLG to TRDC (Cell 4)							
Coarse Sediment from Cell 3	1359	1853	4350	12	775	34	364
Fine Bed Material from Cell 3	2008	2061	10895	484	2223	293	801
Indian Creek (> 8 mm)	62	8	490	0.2	0	35	10
Indian Creek (0.5-8 mm)	127	299	4840	18.7	37	244	285
Weaver/Reading Cks (> 8 mm)	149	19	1176	0	1	85	24
Weaver/Reading Cks (0.5-8 mm)	305	718	11616	45	88	584	683
Bank Erosion (> 8 mm)	778	778	778	778	778	778	778
Coarse Sediment Augmentation	0	0	0	0	0	0	0

The tributary inputs listed in Table 2 differ somewhat from those suggested by Wilcock (2010), which indicated general methods for estimating loads (e.g., rating curves or proportions of watershed area) but provided little detail by which the methods can be evaluated or carried forward. For this budget update, coarse and fine sediment loads delivered from Rush Creek were derived in two ways. GMA monitored suspended and bedload sediment transport in Rush Creek in 2006, and reported total loads for both the 0.5-8 mm and the greater than 8 mm fractions. Those loads are in Table 2. However, in 2007, GMA sampled and reported fractional loads for bedload transport only; for suspended sediment only the total load was reported. Thus, the fraction of the total suspended load in the 0.5-8 mm size class was estimated as the proportion of the suspended load that was in that size class in 2006. All Rush Creek loads for the remaining years were estimated using the rating relations developed by Gaeuman (2008), and documented here in Table 3. Coarse and fine sediment loads for Deadwood Creek were then estimated using the same approach employed by Wilcock (2010), which was to multiply the Rush Creek loads by the ratio of drainage areas in the two watersheds (0.42). Loads for Trinity House Gulch and ungaged south-side tributaries in the Lewiston area not considered by Wilcock (2010) were estimated on the basis of drainage area ratios as 0.25 times the Rush Creek loads (Trinity House Gulch) and 0.18 times the Deadwood Creek loads (Hoadley Gulch, Alder Gulch, Dark Gulch).

Table 3: Rating curves used to estimate Rush Creek and Indian Creek loads. Curves are of the form $Q_s = a(Q - Q_c)^b$, where Q is water discharge in ft^3/s and Q_s is sediment load in tons per day.

	a	*b*	*Qc*	r^2
Rush Creek, 0.5-8 mm	3E-05	2.25	40	0.62
Rush Creek, > 8 mm	2.31E-10	4.05	70	0.48
Indian Creek, 0.5-8 mm	1.46E-06	2.7	0	0.82
Indian Creek, > 8 mm	7.84E-13	4.83	0	0.71

The loads for Indian Creek in Table 2 were estimated in a variety of ways, depending on data availability. No water discharge records are available for Indian Creek in 2004, so the reported loads for that year are those estimated by Wilcock (2010). Loads for 2006 are those reported by GMA, and loads for 2007 were obtained or derived from GMA's WY 2007 report in the same manner already describe for the 2007 Rush Creek loads. Indian Creek loads for the remaining years were computed using a rating curve developed from the 2006 sediment transport data (Table 3). Finally, combined coarse and fine sediment loads for Weaver Creek and Reading Creek, both of which lack streamflow gages, were estimated on the basis of drainage area as 2.4 times the Indian Creek loads, which is also the approach used by Wilcock (2010).

Inputs from Bank Erosion:

The terms quantifying sediment introduced through bank erosion in this budget update differ from the estimates reported by Wilcock (2010). The first and lesser difference is that the estimated inputs of coarse sediment from bank erosion are slightly larger in the present budget than in the Wilcock (2010) budget.

In explaining this difference, it is relevant to note that the bank erosion estimates reported by Wilcock (2010) were originally developed by the present author on the basis of bank undercut depths measured in the field. The methodology was as follows: About 100 points along the Trinity River banks were randomly selected from sections of bank that had previously been mapped in the field as undercut. The selected bank points were located using a GPS, and the depth of the undercut was measured at each point and at an additional point 2 m downstream. Of 190 total measurements, 125 were undercut and 27 of those that were not undercut had fresh erosion faces, suggesting that undercut had recently failed. The average depth of undercut at the bank points that were undercut was 0.46 m and the standard deviation was 0.31 m. These undercuts undoubtedly include places where the undercut had failed in recent years, particularly in areas lacking reinforcement by tree roots (64% of the points with undercuts). In areas with tree roots, the undercuts averaged 0.54 m and had a standard deviation of 0.27 m. These points are also subject to failure, as could be frequently seen where trees had fallen into the channel. It was therefore assumed that an undercut depth of about 0.6 m represents a typical depth of erosion under the tree roots since re-widening of the channel began with the onset of larger restoration flow releases. Maximum undercut depths under trees were about 1.25 m. Because poorly-vegetated banks erode faster than banks reinforced with tree roots and will fail before reaching a large undercut depth, it was assumed that these largest depths represented the typical bank retreat along actively eroding banks. Areas of bank erosion were then calculated by multiplying the lengths of sections of bank mapped in the field as undercut or as actively eroding by these respective bank retreat distances. Volumes of coarse and fine sediment eroded from these banks were then estimated by assuming, from field observation, a typical bank height of 1 m, a sediment porosity of 0.3, that 30% of the bank height is typically composed of coarse sediment, and that the remainder is sandy material. The raw estimates supplied for the earlier report is shown in Table 4.

Table 4: Low end of the range of total estimated bank erosion inputs in tons supplied for 2009 sediment budget by budget cell. Note that estimated fine sediment quantities given in the table include all size fractions < 8 mm.

	< 8 mm	> 8 mm
Lewiston Dam to TRAL (Cell 1)	675	290
TRAL to TRGVC (Cell 2)	9765	4185
TRGVC to TRLG (Cell 3)	15355	6580
TRLG to TRDC (Cell 4)	12830	5450

The bank inputs listed in Table 4 represent the total inputs from bank erosion since relatively large restoration flow releases began, rather than annual rates of input. Wilcock (2010) derived annual coarse sediment inputs by dividing the total bank input estimates equally among the six years spanning 2004-2009, but the sums of those inputs are somewhat smaller than the totals shown in Table 4. Wilcock (2010) did not explain this discrepancy. Moreover, he reported identical bank inputs for both the coarse and fine fractions. The present budget reverts to the original estimates for total coarse sediment inputs shown in Table 4, and divides those totals equally among the seven years spanning 2004-2010. The total inputs were not increased to reflect the passage of another year because there is no new information to support an assumption of continued bank erosion after 2009. These adjustments in the bank erosion terms are of little consequence for the coarse sediment budget because the new values differ relatively little from those used by Wilcock (2010), and the their magnitudes are relatively small compared with mainstem transport rates and gravel augmentation quantities (Table 2).

The second and more important departure from the bank erosion terms used in the Wilcock (2010) budget is that all fine sediment eroded from the stream banks is not considered an input to the stream system. This constitutes a significant change from the Wilcock (2010) analysis, in which bank-derived fine sediments are the largest fine sediment input terms in three of the four budget cells. The decision to exclude the bank erosion terms from the fine bed material budget is justified by consideration of TRRP management objectives for fine-grained sediments and the assessments needed to inform those objectives.

The primary TRRP management objective for fine sediment (< 8 mm) is to reduce storage of those fractions within the TRRP project area. Fine sediments within the Trinity River system reside in essentially two storage compartments: the active channel substrate and as deposits along the channel margins. The channel margin deposits, which frequently take the form of natural levees, constitute the vast majority of these sediments. The TRFES (1999) specifically discusses the need to remove up to 1 million cubic yards of fine sediment stored in these “riparian berms.” The berms were deposited along the channel margins primarily during the first few decades after dam closure, and their removal has been among the principal management objectives for the Trinity River since at least the early 1990s when multiple “feathered edge” bank rehabilitation projects were implemented (TRFES 1999). The relevant questions to ask with respect to this management objective are whether management actions are reducing the quantity of fine sediment stored along the river, and how much of it remains. Partitioning the total fine sediment stored in the system into separate bank and bed storage compartments would contribute nothing toward answering these questions.

A second TRRP management objective with respect to fine sediments is to improve or maintain stream substrate quality by reducing the quantity of fine bed material (0.5-8 mm) stored in the channel bed. To the extent that fine sediment inputs from bank erosion are considered with respect to this management objective, it must be recognized that the bank deposits are composed primarily of material smaller than 0.5 mm in diameter (Wilcock et al. 1996a). The assertion of Wilcock et al. (1996a) that bank deposits are mostly composed mostly of washload is corroborated by bank material samples collected and analyzed following construction of the Indian Creek rehabilitation project in 2007, which indicate that about 88% of the upper banks at that site consist of material finer than 0.5 mm. Thus, only about 12% of the fine sediment quantities given in Table 4 are relevant to this question. Additional sediment samples obtained from other upper bank locations in the study area in the spring of 2011 suggest that the percentage of sediment coarser than 0.5 mm may be even smaller at about 8%. Moreover, it is unclear how considering the transfer of this material from the banks to the channel bed would inform an assessment of substrate quality, and no attempt is made in this report to do so.

In contrast to fine bed material budget, the coarse sediment budget developed in this report incorporates bank storage and storage in the active channel as separate budget components. The primary role of coarse sediment, as envisioned in the TRFES (1999) is to promote alluvial dynamics and the development of complex physical habitat in the active channel. Transferring coarse sediment from bank storage to in-channel storage makes it available for transport and bedform development. Hence, this transfer to the active channel fulfills a management objective, and is considered as an input to the managed system.

Inputs from Debris Flows:

Another fine sediment input included in the Wilcock (2010) budget is an additional 13,000 tons of fine sediment that was lumped with the bank erosion inputs to budget cell 2 in 2006. That extra quantity of sediment accounts for sediment delivery associated with debris flows originating in an area burned by wildfire in 1999 (Madej 2007). The author of the present report estimated the magnitude of the input to the Trinity River by mapping the extent of sand coverage on the channel bed and calculating the volumes of some temporary deltas where debris had entered the Trinity River near Lewiston. That additional supply of fine bed material is retained in the present sediment budget. It should be noted, however, that an unknown portion of the estimated input from this event was finer than 0.5 mm.

Coarse Sediment Augmentations:

The coarse sediment augmentation term for WY 2009 reported by Wilcock (2010) has been adjusted for the present budget update to correct inaccuracies in the net data supplied by TRRP staff when the 2009 budget was being prepared. New coarse sediment quantities included in the updated coarse sediment budget represent high flow injections at the Diversion Pool and the mouth of Grass Valley Creek during the 2010 spring release, plus net gravel additions included in the Sawmill channel rehabilitation project. This budget does not incorporate 17,070 tons of coarse sediment placed in the fall of 2010 during the construction of channel rehabilitation projects at Lowden Ranch, Trinity House Gulch, and Reading Creek. As that material will be inactive until the 2011 spring flow release, it is properly considered a WY 2011 input.

Results

Sediment Budgets, WY 2004-2010

Coarse Sediment:
The cumulative coarse sediment budget for WY 2004-2010 is given in Table 5 and displayed graphically in Figure 2.

Fine Bed Material:

The cumulative fine bed material budget for WY 2004-2010 is given in Table 6 and displayed graphically in Figure 3.

Table 5: Cumulative coarse sediment storage change for WY 2004-2010. Coarse sediment placed during 2010 construction is excluded. See Table 2 for input components.

	2004	2005	2006	2007	2008	2009	2010
Lewiston Dam to TRAL (Cell 1)	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)
Input	3111	42	425	2474	9041	7341	2411
Export	1700	531	8610	93	863	260	550
Cumulative ΔS	1411	922	-7263	-4882	3296	10377	12238
TRAL to TRGVC (Cell 2)							
Input	2472	1131	10167	691	2460	10107	11992
Export	1336	1789	4290	71	1750	470	492
Cumulative ΔS	1136	478	6355	6975	7685	17322	28822
TRGVC to TRLG (Cell 3)							
Input	2276	2729	5230	1011	2690	1410	3727
Export	1359	1853	4350	12	775	34	364
Cumulative ΔS	917	1793	2673	3672	5587	6963	10326
TRLG to TRDC (Cell 4)							
Input	2348	2658	6794	790	1554	932	1176
Export	4869	5229	15200	297	2380	634	1650
Cumulative ΔS	-2521	-5092	-13498	-13005	-13831	-13533	-14007
Total for Cells 1-3	3464	3193	1765	5765	16568	34662	51386
Total for Cells 1-4	943	-1899	-11733	-7240	2737	21129	37380

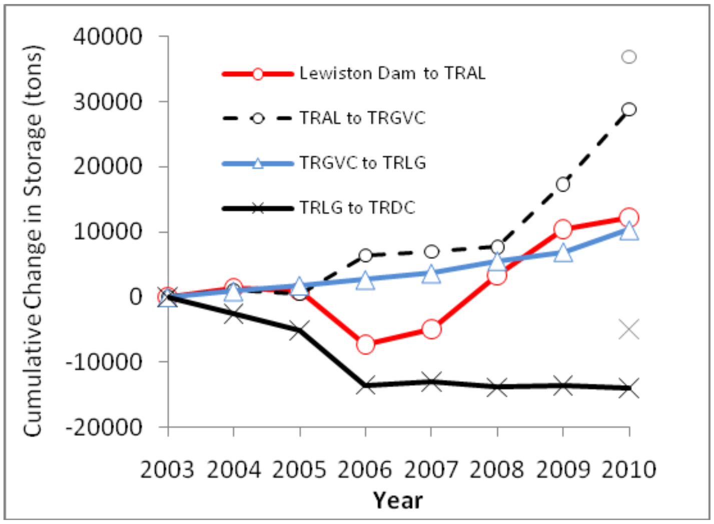

Figure 2: Cumulative changes in coarse sediment storage by budget cell for WY 2004-2010 with zero budget balance assigned to WY 2003. Cumulative changes including fall 2010 construction placements (early WY 2011) in budget cells 2 and 4 are indicated with the solitary symbols.

Table 6: Cumulative fine bed material storage change for WY 2004-2010.

	2004 (tons)	2005 (tons)	2006 (tons)	2007 (tons)	2008 (tons)	2009 (tons)	2010 (tons)
Lewiston Dam to TRAL (Cell 1)							
Input	208	82	1609	48	14	13	41
Export	353	298	1430	113	444	65	39
Cumulative ΔS	-145	-361	-182	-247	-677	-729	-727
TRAL to TRGVC (Cell 2)							
Input	1104	590	18925	187	504	117	197
Export	3190	2908	6070	785	2082	542	377
Cumulative ΔS	-2086	-4404	8451	7853	6275	5850	5670
TRGVC to TRLG (Cell 3)							
Input	3358	2958	7268	815	2090	550	402
Export	2008	2061	10895	484	2223	293	801
Cumulative ΔS	1350	2247	-1380	-1049	-1182	-925	-1324
TRLG to TRDC (Cell 4)							
Input	2440	3078	27351	1235	2348	1121	1769
Export	5452	7024	43800	2393	5340	1354	2650
Cumulative ΔS	-3012	-6958	-21346	-23407	-28244	-28477	-29358

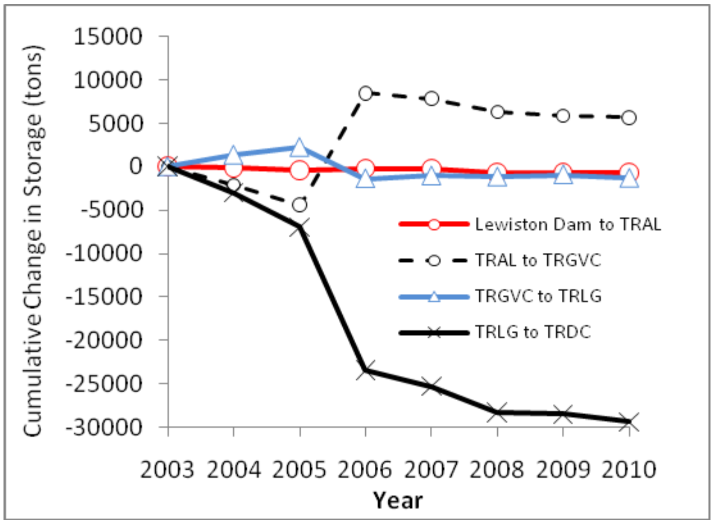

Figure 3: Cumulative changes in fine bed material storage for WY 2004-2010 with zero budget balance assigned to WY 2003.

Wash Load:

As previously mentioned, the present budget follows Wilcock (2010) in that no attempt is made to balance a sediment budget for washload material. However, it has already been pointed out that most of the fine sediment stored in the channel banks is finer than 0.5 mm. As discussed in the TRFES (1999), this finer material is also relevant to habitat quality and channel geometry, and is of management concern. It is suggested here that consideration be given to changing how sediment load estimates are reported in the future to include finer sand fractions in the reported loads of "fine bed material." Currently, all fractions smaller than 0.5 mm are lumped into the < 0.5 mm class in the annual reports prepared by the contractor responsible for sediment sampling and load computations.

Long-term Sediment Budgets

Coarse Sediment Deficit since Dam Closure:

Replacing the total quantity of coarse sediment transported downstream since closure of Trinity Dam – the coarse sediment deficit – is among the management objectives discussed in the TRFES (1999). To assess progress toward that goal, it is necessary to extend the coarse sediment budget back to the time of dam closure in the early 1960s. The actual cumulative deficit is unknown, and estimates of the deficit vary widely. In this section, the long-term storage changes between Lewiston Dam and TRAL and between TRAL and TRLG are quantified by combining the 2004-2010 coarse sediment budgets with estimated storage changes during three time periods: 1961-1980, 1981-2000, and 2001-2003. Budget cells 2 and 3 are combined for this long term budget analysis because sediment monitoring did not start at the TRGVC location until recently, and budget cell 4 is excluded because no data exists with which to estimate changes in coarse sediment storage in that cell prior to 2004. Input, export, and storage change terms for time periods prior to 2004 are derived from five sources: 1) historical coarse sediment augmentations; 2) historical coarse sediment extractions; 3) storage changes for 1981-2000 reported by Wilcock (2004) with corrections as noted below; 4) mainstem transport fluxes approximated on the basis of hydrologic similarity to years after 2003 for which measured transport fluxes are available; 5) estimates of coarse sediment delivery from the principal tributaries near Lewiston Dam, also based on hydrologic similarity to years after 2003.

Coarse sediment augmentation began in the Trinity River as early as 1972. In addition, mechanical dredging of pools in the Trinity River resulted in significant coarse sediment extraction from the river beginning in the mid-1970s. The magnitudes and locations of these activities have been compiled only recently (Appendix A). Net storage changes due to augmentation and extraction for all three time periods prior to 2004 are computed in Appendix A and incorporated in Table 7.

Wilcock (2004) estimated that coarse sediment storage in budget cell 1 decreased by 34,000 tons between 1981 and 2000, and that storage in budget cells 2 and 3 combined decreased by 27,000 tons in the same time period (Table 7). However, numerous large coarse sediment augmentations were either applied inaccurately or absent from the Wilcock (2004) budget, and no dredge extractions were considered. Corrections to the storage changes reported by Wilcock (2004) are computed in Appendix A and incorporated in Table 7.

Mainstem transport fluxes during 1961-1980 are estimated by comparing the total regulated mainstem water discharge during that period to the mainstem hydrology of 2006. With the exception of a few large but brief winter storm events, the regulated stream flows in first two decades following dam closure were generally too small to transport coarse sediments. Wilcock et al. (1996b) found that the minimum discharge to mobilize gravel in the Trinity River ranges between 4,240 ft^3/s and 5,400 ft^3/s. Daily mean discharge at Lewiston during that period equaled or exceeded 4,240 ft^3/s on just 54 days, whereas 5,400 ft^3/s was equaled or exceeded on only 37 days. By comparison, daily mean discharges equaled or exceeded these threshold discharges on 51 (4,240 ft^3/s) and 32 (5,400 ft^3/s) days in WY 2006 alone. It therefore seems reasonable to assume that the total coarse sediment fluxes at TRAL and TRLG over that 20-year period were similar to the fluxes measured at the same locations in 2006. This suggests that the total mainstem exports from budget cell 1 during 1961-1980 was about 8,600 tons, whereas mainstem inputs to budget cells 2 and 3 may have exceeded mainstem exports by about 4,200 tons (Table 7).

Mainstem transport fluxes in 2000 through 2003 were also estimated on the basis of hydrologic similarity with later years. WY 2001, 2002, and 2003 were dry, normal, and wet, respectively. Extrapolating export loads measured at TRAL and TRLG during years of the same hydrologic type from 2004-2010 suggests that roughly 2,500 tons of coarse sediment was exported from budget cell 1 and input to the budget cells downstream, and another 2,500 tons was exported downstream from budget cell 3 (Table 7).

Stream flows in Deadwood Creek and Rush Creek, the principal tributaries that deliver coarse sediment upstream from TRLG, have remained unregulated throughout the post-dam era. Inputs of coarse sediment from these sources were estimated for 1961-1980 and 2000-

2003 by extrapolating their coarse sediment inputs estimated for dry, normal, wet, and extremely wet water year types in 2004-2010 to the water year type recorded in each of the earlier years (Tables 7 and 8). Coarse sediment delivery from Grass Valley Creek, which tends to produce a large proportion of sand and very fine gravel bedload (Trso 2004), is assumed to be zero in all years.

Combining all the estimated storage changes described above brings the total coarse sediment deficit accumulated between dam closure and the end of 2003 to 20,783 tons in budget cell 1 and 66,340 tons in budget cells 2 and 3 combined (Table 7). Setting the origin for the 2004-2010 coarse sediment budgets to these deficit values yields estimated net changes in sediment storage between closure of Trinity Dam and the end of 2010 of 8,543 tons in budget cell 1 and 27,190 tons in budget cells 2 and 3 (Table 7, Figure 4).

Table 7: Coarse sediment budget terms and cumulative storage changes in budget cell 1 and in budget cells 2 and 3 combined since dam closure as of the end of WY 2010. Coarse sediment placed during 2010 construction is excluded.

	Budget Cell 1 (Dam to TRAL)	Budget Cells 2 and 3 (TRAL to TRLG)
1961-1980		
Input from upstream (tons)	0	8600
Tributary Input (tons)	1400	3500
Export (tons)	8600	4400
Augment. – Dredge (tons)	16897	-4745
1980 Deficit (tons)	9697	2955
1981-2000		
ΔS per Wilcock (tons)	-34000	-27000
Augment. – Dredge (tons)	31450	-43345
Adjustment to Wilcock ΔS (tons)	-27430	0
2000 Deficit (tons)	-20283	-67390
2001-2003		
Input from upstream (tons)	0	2500
Tributary Input (tons)	140	175
Export (tons)	2500	2500
Augment. – Dredge (tons)	2000	1050
2003 Deficit (tons)	-20783	-66340
2004-2010		
ΔS (tons)	12240	39150
2010 Deficit (tons)	-8543	-27190

Table 8: Estimated annual coarse sediment inputs from tributaries by water year type in 2004-2010, and estimated total inputs by period for 1961-1980 and 2000-2003. Deadwood Creek delivers to budget cell 1 and Rush Creek delivers to budget cell 2.

2004-2010	Number Years	Deadwood Creek Average Input (tons)	Rush Creek Average Input (tons)
Dry	2	0.5	0.7
Normal	3	0.33	1.0
Wet	1	70.0	175.0
Extremely Wet	1	384.0	960.0
1961-1980		Deadwood Creek Period Total (tons)	Rush Creek Period Total (tons)
Dry	4	2.0	2.8
Normal	4	1.3	4.0
Wet	9	630.0	1,575.0
Extremely Wet	2	768.0	1,920.0
Period Total (rounded)		1,400.0	3,500.0
2000-2003			
Dry	1	0.5	0.7
Normal	1	0.3	1.0
Wet	2	140.0	175.0
Period Total (rounded)		140.0	177.0

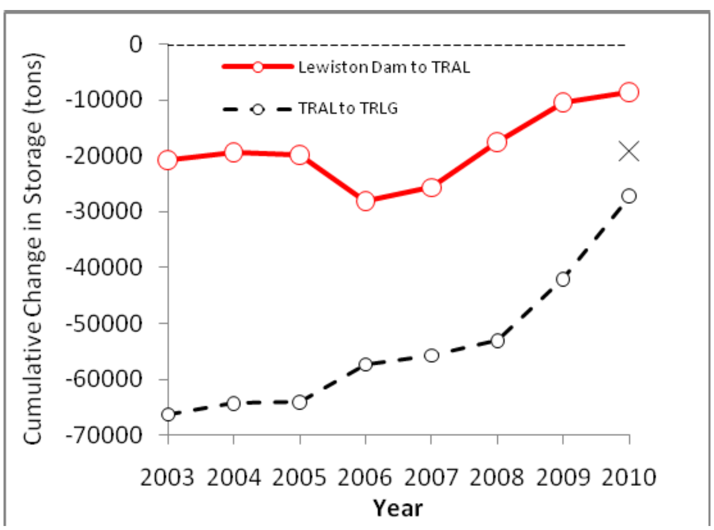

Figure 4: Cumulative changes in coarse sediment storage since dam closure in the budget cell 1 and the budget cells 2 and 3 combined as of the end of WY 2010. The X indicates the cumulative change in budget cells 2 and 3 as of January 2011, prior to the 2011 high flow release.

Fine Bed Material Surplus:

The long-term fine bed material budget discussed in this section pertains to all budget cells 1-4, that is, the entire river segment between Lewiston Dam and TRDC. The first few decades following dam closure are known to have been a period of fine sediment deposition in the reaches downstream from the dams, as evidenced by significant channel narrowing and the formation of berm-like natural levees (Wilcock et al. 1996; TRFES 1999). In addition, pools were significantly filled and spawning riffles were choked with sandy bed material for a distance of at least 8 miles immediately below Grass Valley Creek (CRA 1970), a watershed that has historically delivered copious quantities of fine sediments derived from decomposed granite. Fine sediment delivery to the Trinity River was reduced substantially since the 1980s by watershed restoration activities in the Grass Valley Creek watershed and operation of the Hamilton Ponds at the mouth of Grass Valley Creek (Trso 2004).

Among the major reservoirs of fine bed material storage in the riverine system at present is in natural levee deposits along the stream banks. The TRFES (1999) suggested that about 1 million cubic yards (1.5 million tons) of fine sediment may have accumulated in these deposits, which it refers to as riparian berms. These figures were based on the assumption that post-dam riparian berms 3 feet high and 20 feet wide line both banks of the river the entire distance between Lewiston Dam and the North Fork Trinity River. As previously mentioned, sediment samples from the Indian Creek rehabilitation site indicated that only about 12% of these bank deposits are in the fine bed material size range. Using this percentage, it is calculated that about 180,000 tons of fine bed material was stored along the channel margin between 1960 and 1980. However, only about 45% of the stream length upstream from the North Fork Trinity River is upstream from TRDC, so the equivalent storage estimate for budget cells 1 through 4 is 81,000 tons.

A more refined estimate of this storage quantity can be derived using a geomorphic map produced by the Hoopa Valley Tribe in 2003. That map indicates that berms actually occupy only about 22 miles (less than one quarter) of the bank length between Lewiston Dam and the North Fork Trinity River, and less than half of that is located upstream from TRDC. Multiplying a berm length of 11 miles by the same average berm dimensions assumed in the previous estimate yields about 130,000 cubic yards of berm deposits, or 175,000 tons. After scaling by the fraction of the berm deposits larger than 0.5 mm in diameter, a storage quantity of 21,000 tons of fine bed material is obtained.

It is likely that that fine bed material storage in the upper reaches of the Trinity River reached a maximum in the 1970s or early 1980s, as regulated stream flows were lowest and least effective for removing fine sediments during the first two decades following dam closure. Excess sandy sediment deposited on the surface of the active channel bed likely comprised a major reservoir of fine bed material storage at that time. Qualitative accounts imply that the much of the bed of the Trinity River was covered in fine bed material for several miles in the vicinity of Grass Valley Creek (CRA 1970). Assuming that an active bed width of 90 feet was buried to an average depth of 0.5 feet for a distance of 8 miles, and given a bulk density of the deposits of 1.5 tons per cubic yard, a quantity of fine bed material exceeding 100,000 tons of may well have been stored on the channel bed. However, this computation cannot be verified, and in any case, the stream bed has since reverted to a dominantly gravel-cobble substrate. Whatever the quantity of fine sediments stored in the active channel in past decades, it had been largely removed by the beginning of this century. Thus, the long-term fine bed material budget does not consider surplus sand stored on the active channel bed. Instead, it considers only the surplus fine bed material stored in the berm deposits noted in the TRFES (1999). Both estimates of fine bed material storage in berms outlined above – one derived directly from the TRFES (1999) and one based on the mapped distribution of berm deposits – are carried forward in the long-term fine bed material budget. The first provides an upper bound on the post-dam accumulation of these size fractions in riparian berm deposits, whereas the later is treated here as a lower bound. It is assumed that all berm deposits that had accumulated in the study area since dam closure were still present in 2000, so a decrease in fine sediment storage prior to 2000 reported by Wilcock (2004) is neglected in this analysis.

Extrapolating the calculated changes in fine bed material storage upstream from TRDC in dry, normal, and wet water years since 2004 suggests that storage decreased by 9,270 tons between 2000 and 2004. Subtracting this figure from the upper and lower bounds estimated for the year 2000 yields a range of excess fine bed material storage quantities at the beginning of 2004 of 11,730 to 71,730 tons. Adding in the total storage changes computed for budget cells 1 through 4 since 2004 completes the long-term budget. The resulting estimates of fine bed material storage relative to conditions at the time of dam closure range from an excess of about 46,000 tons to a deficit of about 14,000 tons (Figure 5).

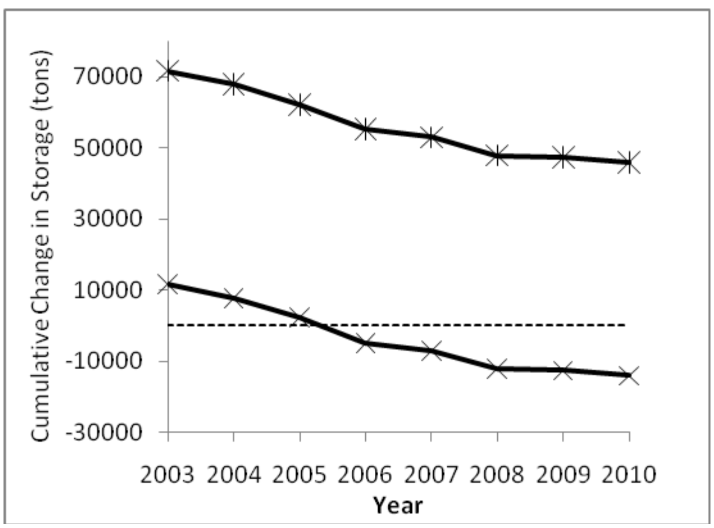

Figure 5: Alternative estimates of cumulative changes in fine bed material storage since dam closure upstream from TRDC at the end of WY 2010, based on alternative estimates of excess fine bed material storage in riparian berms (described in the text).

Discussion

Coarse Sediment Management

<u>Coarse Sediment Storage Changes since WY2003:</u>

The coarse sediment budget indicates that recent TRRP management actions have produced an increase in coarse sediment storage in three of the four sediment budget cells downstream from Lewiston Dam since 2003. The largest increase (nearly 29,000 tons) was found in budget cell 2 (TRAL to TRGVC), where channel rehabilitation activities have been most concentrated over the past several years. Storage in budget cell 1 (Lewiston Dam to TRAL) decreased markedly in 2006 from a slight positive in 2005 balance to about -7,000 tons as a result of the large spring release that year, which peaked at about 10,300 ft^3/s. However, coarse sediment augmentation activities in budget cell 1 since 2006 have rapidly increased storage by about 20,000 tons to a current cumulative positive balance of more than 12,000 tons. Storage increases in budget cell 3 (TRGVC to TRLG) since 2003 have been more gradual, as very little coarse sediment augmentation has been implemented in this cell. In fact, the net increase in coarse sediment storage in budget cell 3 of 10,326 tons is 4.5 times larger than the total quantity of coarse sediment augmentation in the cell (2,295 tons). More than ¾ of the increase is due to mainstem transport from upstream. This is an important result, as it implies that coarse sediment supplies in budget cell 2 are gradually being propagated downstream into cell 3 by natural river processes, but have yet to reach the downstream boundary of the cell. The exception to the recent trend toward increasing coarse sediment storage is budget cell 4 (TRLG to TRDC), which has shown a consistent decline since 2004 to its current cumulative deficit of about -14,000 tons. This result has important management implications, particularly with respect to a question that has recently surfaced regarding possible coarse sediment augmentation downstream from Indian Creek.

The relative magnitudes of these storage changes can be assessed in terms of storage changes per river mile and equivalent bed elevation changes in each budget cell. Storage increases per river length and in terms of bed elevation changes have in cells 1 and 2 since 2003 have been roughly equivalent at approximately 6,100 and 5,450 tons/mile, respectively, and an average of about 0.18 ft of aggradation over the cell bed areas (Table 9). Cell 3 experienced about 1/3 the relative storage increase of the upstream cells, with an increase of about 1,700 tons/mile and average bed aggradation of about 0.06 ft. Likewise, the relative storage decrease in cell 4 was slightly more than 1/3 the magnitude of the changes in cells 1 and 2, with a decrease in storage of about 2,200 tons/mile and average bed incision of about 0.08 ft. Similar comparative statistics for fine sediment storage and for storage changes over other time intervals can be calculated using the cell lengths and channel areas reported in Table 9. Channel areas reported here are based on the wetted channel area plus emergent in-channel bar area as mapped with terrestrial LiDAR in April 2009 when discharge was 300 ft^3/s.

Questions have been raised regarding whether a coarse sediment deficit exists downstream from Indian Creek and whether reaches below Indian Creek might benefit from coarse sediment augmentation. The consistent decrease in storage observed in budget cell 4 is a strong indication that the answer to these question is no. The average coarse sediment export from cell 4 during 2004-2010 (4,322 tons) is 3.4 times the average mainstem input from budget cell 3 (1,250 tons), indicating that the supply of mobile coarse sediment increases substantially somewhere upstream from TRDC. Most likely, that increase is associated with the confluences of Indian Creek, Weaver Creek and Reading Creek. All three of these tributary confluences are located within budget cell 4 (Figure 1).

Table 9: Cumulative coarse sediment storage changes since 2003 per cell length and as equivalent bed elevation change (ΔZ). ΔZ is computed assuming a bulk coarse sediment porosity of 0.4.

	Cell 1	Cell 2	Cell 3	Cell 4
Cell River Length (miles)	2.0	5.3	6.1	6.4
Cell Channel Area (acres)	31.4	74.9	83.2	86.4
Cumulative ΔS, tons/mile	6119	5438	1693	-2189
Cumulative ΔZ, feet	0.16	0.16	0.05	-0.07

Moreover, it is likely that the reaches immediately downstream from those confluences have stored surpluses of coarse sediment since dam closure due to the reduced transport capacity of regulated mainstem flows. The average rate of tributary input of coarse sediment to cell 4 shown in Table 2 is 1,640 tons/yr. Assuming this figure is representative of the 43 years between dam closure and 2004, an estimated 70,500 tons of coarse sediment was delivered from those three unregulated tributaries to their confluences with the Trinity River by 2003. At the same time, persistent low flows due to regulation by the dams resulted in minimal mainstem coarse sediment transport for most of those 43 years. The average peak discharge at Lewiston during that time period was just 3,352 ft^3/s. For comparison, the average peak discharge and total coarse sediment export from cell 4 during two dry years in 2004-2010 were 4,690 ft^3/s and 465 tons/yr, respectively. Extrapolating that annual export rate over 43 years suggests that a total of about 20,000 tons of coarse sediment was exported from cell 4 by mainstem flows by 2003. As an alternative comparison, the estimated cumulative export from cell 1 during the same 43 years is 45,100 tons (Table 7). These two estimates of mainstem export totals constitute 28% and 65% of the tributary deliveries to cell 4, respectively. On the basis of these considerations, it is postulated that the recent decrease in coarse sediment storage observed in budget cell 4 represents a recovery from post-dam aggradation rather than growth of a coarse sediment deficit.

The recent decrease in coarse sediment storage in budget cell 4 notwithstanding, there has been an overall increase by 37380 tons in the combined coarse sediment storage for all 4 budget cells upstream from TRDC since 2003, and an even larger increase for the 3 cells upstream from TRLG (Figure 6).

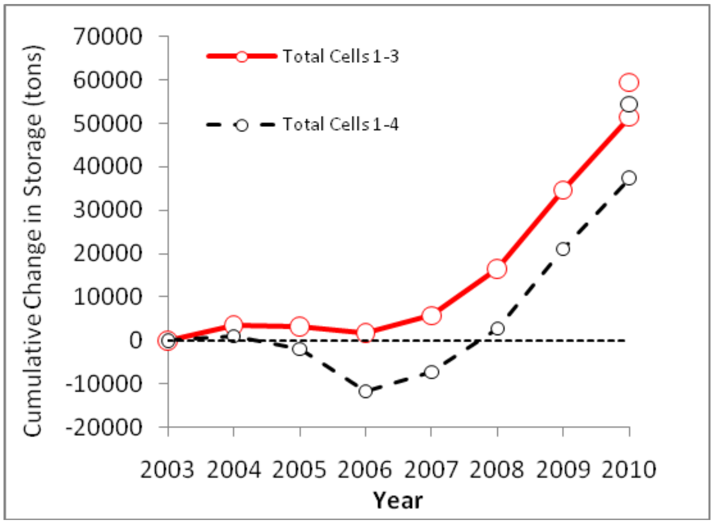

Figure 6: Cumulative total changes in coarse sediment storage in cells 1-3 and cells 1-4 since WY 2003. Cumulative changes including fall 2010 construction placements (early WY 2011) in budget cells 2 and 4 are indicated with the solitary symbols.

Coarse Sediment Storage Changes since Dam Closure:

Long-term coarse sediment budgets suggest that any coarse sediment deficit that may have developed in budget cell 1 following dam closure has been reduced to a quantity on the order of what the river can transport in a single year. The net coarse sediment deficit calculated since 1960 in budget cells 1 of 8543 tons is slightly smaller than the coarse sediment flux measured at TRAL during the 2006 release. The relatively small deficit calculated for budget cell 1 is largely due to 19th-century dredging and coarse sediment replacement activities that resulted in the transfer of more than 48000 tons of coarse sediment dredged from more downstream locations to budget cell 1 between 1972 and 1991.

The same dredging and coarse sediment replacement operations that contributed to deficit reduction upstream from TRAL depleted coarse sediment storage in downstream reaches. The 2010 coarse sediment deficit of 27190 tons computed for budget cells 2 and 3 is entirely due to the these operation, which removed about 48000 tons of coarse sediment from that section of the river. Nonetheless, the 2010 deficit is considerably smaller than those losses (about 56%), and is relatively modest in terms of deficit per unit area. The 2010 deficit implies that the net decrease in the channel bed elevation in cells 2 and 3 since dam closure is just 0.07 feet. The 2010 deficit is also relatively small compared with the coarse sediment deficits calculated for the preceding two time periods, which were about two and a half times larger. It is anticipated that the 2011 spring flow release will further reduce the coarse sediment deficit in these two budget cells, as transport rates across the upstream boundary of cell 2 are likely to exceed transport rates across the downstream boundary of cell 3.

Maintenance of Coarse Sediment Storage:

Apart from trying to eliminate any coarse sediment deficit that may exist in the budget cells upstream from TRLG, TRRP also seeks to maintain coarse sediment storage volumes by adding at least as much coarse sediment to the river as is exported downstream during the annual high flow releases. Much of the storage increases achieved in recent years has been accomplished through bar construction during channel rehabilitation projects. Maintenance of coarse sediment transport rates into the future will likely be achieved through annual high-flow coarse sediment injections at a few sites. At least four of these so called “long-term“ sites have been identified to date.

The most upstream long-term site is the Diversion Pool, which is in the middle of budget cell 1 at the locations of the USGS stream gage 11525500 shown on Figure 1. Coarse sediment transport out of cell 1 during 2004-2010 has averaged 1,800 tons/yr, which is a flux rate that could be maintained from injections at this single location. It is assumed that the flux rate for those seven years represents a reasonable long-term average because the average peak flow during that period (6,800 ft^3/s) has an expected return frequency of about 2.3 years under current dam operating plans. TRRP began using this site to inject about 2,000 tons of coarse sediment per year in 2008. The injections caused some problems with the USGS stream gage just downstream, but the site otherwise accepts this volume of material with no ill effects. The stream gage has now been relocated farther upstream. A potential second long-term site in budget cell 1 is the Cableway reach just upstream from TRAL. However, given the effectiveness of the Diversion Pool site, the Cableway site may or may not be needed in the future.

To date, only one long-term coarse sediment augmentation site has been used in budget cell 2 (the Sawmill site). However, recent rehabilitation projects in cell 2 have included very large coarse sediment additions: about 18,800 tons of coarse sediment were added to budget cell 2 in just the past three years. The vast majority of that coarse sediment was placed in the immediate vicinity of the Sawmill augmentation site, near the cell’s upstream boundary. Sediment monitoring data from those same three years shows that the total coarse sediment transport out of cell 2 was just 1,173 tons, suggesting that the recently-added coarse sediment has not yet propagated to the downstream portion of the cell. Given the possibility that most of that coarse sediment remains concentrated in the upper portion of the cell near the Sawmill augmentation site, it may be prudent to reduce the rate of coarse sediment addition there. Continued input could risk adverse consequences, such as local aggradation that could contribute to flooding, bank erosion, navigation difficulties, and the filling of holding pools used by adult fish.

Fine Bed Material Management

Fine Bed Material Storage Changes since WY2003:

Fine bed material budgets for 2004-2010 indicate that TRRP management actions have produced a large decrease in fine bed material storage in budget cell 4. However, fine bed material storage has remained essentially constant in budget cells 1 and 3, and increased by about 5,000 tons in budget cell 2 (Figure 3). The increase in budget cell 2 occurred entirely in WY2006 and is a direct result of debris flows that delivered large quantities of fine bed material to the river from an area burned by wildfire a few years before. Storage in cell 2 has been slowly declining in the years since. To some extent, the fact that fine bed material storage does has not decreased in budget cells 1 through 3 in recent years may be due to a relative scarcity of fine sediment stored in those cells. Conversely, the large decrease in cell 4 may reflect the fact that in that larger quantities of fine bed material are presently stored in that cell. In fact, most of the berm deposits that hold large quantities of fines adjacent to the river channel are found downstream from TRLG.

Fine Bed Material Storage Changes since Dam Closure:

A somewhat longer-term fine bed material budget based measured fine bed material loads for 2004-2010 and peak flow magnitudes for 2000-2003 suggests that the quantity fine bed material stored upstream of TRDC may be approximately equal to or less than the quantity of that size fraction present in the same section of river prior to dam closure. Depending on what assumptions are made concerning the extent of fine berm deposits along the river, the current quantity of fine bed material (0.5-8 mm) stored between Lewiston Dam and TRDC relative to pre-dam storage levels is between 46,000 tons to -14,000 tons. The smaller (negative) figure is likely the more accurate estimate, as the maximum post-dam storage level used in that calculation was estimated using the mapped distribution of berm deposits. The larger figure was derived using the unrealistic assumption that berms occupy 100% of the bank length on both sides of the river.

This result, which is based on annual sediment transport monitoring, implies that the combination of high flow releases and watershed restoration has been successful for reducing fine bed material storage upstream from TRDC. This inference is supported by field observation indicating that recent high flow releases are effective for removing sand size fraction from the surface of the active channel bed and that banks show evidence of recent erosion in many areas. In addition, bulk substrate sampling conducted in 2009 suggests that the fraction of sand in the subsurface may also be declining (GMA 2010).

Sediment Budget Uncertainty and Sensitivity Analysis

The mainstem sediment fluxes reported by GMA and the coarse sediment augmentations implemented by TRRP are the largest components of the coarse sediment budget by a wide margin. Augmentation volumes are known to a relatively high degree of precision, and it is assumed that those quantities are free of error. The accuracies of the sediment fluxes reported by GMA, however, are subject to significant uncertainty. The potential error in mainstem flux estimates was evaluated by considering the variability between different successive sampling passes conducted at the same site on the same day over a constant discharge level. Inspection of bedload transport data at all sites over all years sampled reveals that successive coarse sediment samples obtained when flows were within 0.8 times the peak flow differed by a factor of 2.17 on average. Assuming all of this difference is due to error and that the true coarse sediment flux rate was the mean of the two successive passes, this result implies that each sample pass incorporates an error equal to about 50% of the true value. Therefore, a potential error magnitude of ±50% is assumed for all mainstem sediment fluxes reported by GMA. The remaining components of the sediment budgets (tributary inputs, bank erosion inputs, and fire-related debris flow) are subject to greater uncertainty. Potential errors of ±100% are assumed for those budget terms. Independent budget components are then compounded and cumulated through time as the square root of the sum of squared error sources:

$$\delta = [\Sigma(\varepsilon_i^2)]^{0.5}, i = 1 \text{ to } n$$

where ε_i represents the i^{th} error source term and δ is a cumulative error compounded over n independent error terms. Error source terms include all inputs and exports when computing δ for individual cells, whereas internal cell boundary fluxes are excluded from the error source sums when computing δ for groups of cells. The resulting error margins cumulated over the 2004-2010 short-term budget period are given in Table 10.

Error margins over the short-term (2004-2010) coarse sediment budgets were found to be consistently much smaller than the total calculated changes in storage (Table 10). This result suggests a high degree of confidence in the general results described above, that is, coarse sediment storage increased throughout cells 1-3 during 2004-2010, and decreased in cell 4. Less confidence can be placed in the short-term fine bed material budget, as error margins are similar in magnitude to the calculated storage changes. However, it can be stated with reasonable confidence that fine bed material storage levels through cell 1-4 either decreased or remained approximately constant over the 2004-2010 time period.

The error margins computed for 2004-2010 are extended to cover the time period of 2001-2010 by incorporating the mainstem error source terms for 2004, 2007, and 2010 a second time. This extrapolation procedure is consistent with the method used to estimate sediment fluxes for 2000-2003 when no sediment monitoring was preformed. No attempt has been made to estimate error bounds on the sediment storage changes presented by Wilcock (2004), as a thorough investigation into the quality of data and analysis supporting that work is beyond the scope of this study. Instead, the potential error margins are extended to cover the period between dam closure and 2000 by incorporating the mainstem error terms for the extremely wet year of 2006 three more times: once to represent sediment transport between dam closure and 1980 and twice more to represent sediment transport during the 1980s and 1990s, respectively. Coarse sediment dredge totals presented in Table A-2 have been assigned error bounds of ±20% as noted in Appendix A. All pre-2004 tributary input estimates are assumed to incorporate errors of up to ±100%.

Although the resulting error estimates are admittedly extremely rough, they are almost certainly larger than the actual cumulative errors. Comparisons between computed sediment balances and the cumulative error margins supports the previously-stated results that coarse sediment storage has increased substantially in budget cells 1-3 since 2003, and that coarse sediment storage in budget cell 4 has decreased (Table 10). It also supports the conclusion that any remaining post-dam coarse sediment deficit that may have existed in budget cell 1 has been greatly reduced, or even reversed. The long-term coarse sediment deficit calculated for budget cells 2 and 3, however, is larger than the probable error magnitude, indicating that the actual coarse sediment storage change since dam closure is almost certainly negative. A near equality between the computed reduction in fine bed material storage during 2004-2010 and the potential error in that computation supports the conclusion that fine bed material storage has either decreased or remained approximately constant over the short term. Conversely, the potential error in the long-term fine bed material budget is much larger than the calculated net storage change since dam closure for those size fractions, so little confidence can be placed in any conclusion regarding whether a post-dam fine bed material excess still exists in the study area.

Table 10: Final cumulative sediment storage changes as of 2010 and associated uncertainty margins. *Storage change figure is for 1980-2004 and corresponds to the lower of the two lines plotted on Figure 5.

	$\Delta S \pm \delta$, 2004-2010 (tons)	$\Delta S \pm \delta$, 1960-2010 (tons)
Lewiston Dam to TRAL (Cell 1)		
Coarse Sediment (> 8 mm)	12238 ± 4450	-8543 ± 18190
Fine Bed Material (< 8 mm)	-727 ± 1800	
TRAL to TRGVC (Cell 2)		
Coarse Sediment (> 8 mm)	28822 ± 5460	
Fine Bed Material (< 8 mm)	5670 ± 5600	
TRGVC to TRLG (Cell 3)		
Coarse Sediment (> 8 mm)	10326 ± 4380	
Fine Bed Material (< 8 mm)	-1324 ± 7650	
TRLG to TRDC (Cell 4)		
Coarse Sediment (> 8 mm)	-14007 ± 9210	
Fine Bed Material (< 8 mm)	-29360 ± 26520	
TRAL to TRLG (Cells 2-3)		
Coarse Sediment (> 8 mm)	51386 ± 5960	-27190 ± 18760
Lewiston Dam to TRDC (Cells 1-4)		
Fine Bed Material (< 8 mm)	-25740 ± 26260	-14000* ± 57700

Beyond the numerical uncertainties discussed above, the present budget incorporates a number of shortcomings that could be addressed in future budget updates. Perhaps the most significant of these is that sediment delivery during a large storm in December 1964 is not explicitly considered. That event, during which inflows to Trinity Lake were estimated to exceed 100,000 ft^3/s (Stearns 1969), produced up to 11 feet of aggradation at tributary confluences between Lewiston Dam and the North Fork Trinity River, as well as lateral bank erosion of up to 140 feet (Ritter 1968). Another potentially significant issue is that in-channel sand and gravel mining occurred in several locations throughout the study area from the 1950s into the 1980s. Two of these extraction operations were located in the Douglas City area. However, little information is available to evaluate their influence on sediment storage in budget cell 4.

Estimates of mainstem sediment fluxes for years prior to 2004 when annual transport measurements became available are rough approximations based on gross streamflow statistics. Their accuracy could be improved by computing transport from daily streamflow records. The same may be true of many of the tributary input estimates, although the paucity of data quantifying tributary transport rates greatly limits the confidence that can be assigned to those estimates irrespective of the analysis methods employed. The present budget also includes no error margins for the storage changes reported by Wilcock (2004). Future updates to the sediment budget could include a more thorough review of the Wilcock (2004) budget with an eye toward estimating error bounds. Better evaluation of sediment dynamics related to bank erosion and other planform changes is needed. In particular, sediment transfers related to growth of the Rush Creek delta and associated planform changes should be considered.

Conclusions and Recommendations

Sediment budget calculations incorporate substantial uncertainties. Annual sediment transport monitoring is needed to continue tracking sediment storage changes into the future.

Short-term coarse sediment budget calculations suggest that coarse sediment augmentations since 2003 have substantially increased coarse sediment storage in budget cells 1 through 3 (Lewiston Dam to TRLG).

Coarse sediment storage has decreased in budget cell 4 (TRLG to TRDC) since 2003. This decrease probably reflects the evacuation of excess sediment stored downstream from tributary confluences after dam closure.

A large increase in coarse sediment transport rates at TRDC compared with other sediment monitoring locations indicates that the coarse sediment supply at TRDC is much larger than at the upstream locations. These data support existing management guidelines asserting that coarse sediment augmentation is unnecessary downstream from Indian Creek.

Long-term budget calculations suggest that any coarse sediment deficit that may have developed in budget cell 1 (Lewiston Dam to TRAL) has been greatly reduced, or even eliminated.

A long-term coarse sediment deficit equivalent to an average channel bed incision of 0.07 feet remains in budget cells 2 and 3 (TRAL to TRLG). This deficit can be attributed to historical dredging activities, as well as to fluvial transport of coarse sediment.

Recent rates of coarse sediment augmentation in budget cell 2 are much greater than the rate of downstream transport. Slowing the augmentation rate in at that location should be considered.

Current coarse sediment transport rates at the TRAL sediment monitoring location can likely be fully maintained with annual high-flow injections at the Diversion Pool augmentation site.

Increasing coarse sediment storage in budget cell 3 (TRGVC to TRLG) suggests that coarse sediment augmentations may have contributed to increased transport rates as far downstream as TRGVC, but have not yet influenced transport rates at TRLG.

Fine bed material budget calculations show that high flow releases in combination with watershed restoration are effective for removing excess fine bed material stored upstream from TRDC.

A large proportion of the fine bed material surplus stored in berms along the channel margins downstream from Lewiston Dam since dam construction appears to have been evacuated. The quantity of surplus fine bed material stored in berms upstream from TRDC is probably less than 50,000 tons, and may be near zero.

Program monitoring protocols for assessing fine sediment transport may be in need of revision. Fine bed material is defined by the size fractions between 0.5 and 8 mm on the basis of materials found in the stream bed. However, that size range is a minor component (~12%) of the bank deposits that constitute the majority of the fine sediment stored in the TRRP project area. Removal of these bank deposits (berms) is a major management focus. It is recommended that the inclusion of smaller sand fractions in the sand and fine gravel loads reported by the sediment monitoring contractor be considered. This adjustment would permit development of a sediment budget that better reflects the composition of the material stored along the channel margins.

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APPENDIX A: Historical Coarse Sediment Augmentation and Extraction

Various government agencies have been engaged in stream rehabilitation activities in the Trinity River downstream from Lewiston Dam since the early 1970s. Among those activities was the dredging of pools, both to remove sand from the system and to create holding habitat for adult salmonids. Dredging sometimes removed coarse sediment from the stream bed, which was commonly separated from the finer bed material and placed back into the channel to construct spawning riffles. Among the results of this practice was a net transfer of coarse sediment upstream, as material dredged at downstream locations was replaced in the river nearer Lewiston Dam.

A large number of archived documents, including work plans, contract invoices, and reports were recently compiled and analyzed to construct an historical record of these past dredging and augmentation activities. Results of the investigation pertinent to the 2010 coarse sediment budget are summarized in Table A-1.

Table A-1: Coarse sediment dredge and augmentation quantities in the Trinity River from dam closure through 2001. Year given is the year of the first spring flow event following implementation.

	Cell 1		Cells 2-3	
Year Effective	Additions (tons)	Dredge (tons)	Additions (tons)	Dredge (tons)
1973	8100			
1977	17474	2770	7488	5215
1978	1910	5135	7666	11260
1979		630		3245
1980	1695	3750	2070	2250
1981	15356	1385	2194	4125
1982	300		450	
1983				
1984	4050		900	2925
1985	2642			12000
1986		1385		6620
1987	2453			2465
1988				2700
1989				7500
1990	4463		1200	7495
1991	1755			2265
1992				
1993				
1994				
1995				
1996				
1997				
1998				
1999	2200			
2000	1000			
2001	2000		1050	

Augmentation quantities given in Table A-1 are believed to be accurate. However, many of the records documenting dredge quantities report total sediment only, such that some coarse sediment quantities are derived using estimated proportions of gravel in the totals. Coarse sediment dredge totals may therefore incorporate potential errors of up to 20%. Details regarding these historical dredging and augmentation activities, including project locations, data sources, and analysis methods, will be given in:

Krause, A. (in preparation). Mechanical extraction and augmentation of in-channel sediment on the Trinity River, California, 1950-2011. TRRP Technical Report TM-2011-3, Trinity River Restoration Program, Weaverville, CA.

The long-term coarse sediment budget incorporates the net differences between coarse sediment augmentation and dredge quantities in budget cell 1 and in budget cells 2-3 in each of the following three budget periods: 1961-1980, 1981-2000, and 2001-2003. The budget period spanning 1981-2000 also incorporates an adjustment to the storage change in budget cell 1 reported by Wilcock (2004). This adjustment is necessary because Wilcock (2004) included a portion of the pre-1980 augmentation quantity in his 1981-2000 budget calculations. In addition, a large portion of the pre-1980 augmentations was added to budget cell 2, whereas Wilcock assigned all material to budget cell 1. Table A-2 summarizes net dredge-augmentation quantities and other adjustments to the long-term coarse sediment budget. Net adjustment quantities are incorporated in Table 7.

Table A-2: Adjustments to the long-term coarse sediment budget by budget cell and budget period.

	1961-1980	1981-2000	2001
Budget cell 1			
Augmentation (tons)	29180	34220	2000
Dredge (tons)	12285	2770	0
Net Augmentation – Dredge (tons)	16897	31450	2000
Augmentation per Wilcock (tons)	na	27430	Na
Adjustment to Wilcock ΔS (tons)	na	-27430	Na
Budget cells 2, 3			
Augmentation (tons)	17225	4745	1050
Dredge (tons)	21970	48090	0
Net Augmentation – Dredge (tons)	-4745	-43345	1050
Augmentation per Wilcock (tons)	na	0	Na