Mapping Prehistoric, Historic, and Channel Sediment Distribution, South Fork Noyo River: A Tool For Understanding Sources, Storage, and Transport[1]

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Abstract

The South Fork Noyo River (SFNR) watershed in coastal northern California contains large volumes of historic sediment that were delivered to channels in response to past logging operations. This sediment presently is stored beneath historic terraces and in present-day channels. We conducted geomorphic mapping on the SFNR valley floor to assess the volume and location of sediment associated with pre-historic terraces, historic terraces, and the active channel along four 1-mi-long stream reaches. Additionally, we established ten streamflow and suspended sediment sampling locations to monitor water and sediment discharges. We estimate 158,000 yds^3 of sediment stored in the active channel, and 68,000 yds^3 of sediment stored beneath historic terraces. These volumes are an order of magnitude less than the volumes estimated for pre-historic terraces. The present-day channel sediment is stored presently in large gravel bars and is mobilized primarily during winter flood events.

Based on channel mapping and hydrologic data, we infer that the largest suspended sediment loads are spatially coincident with the locations of the greatest amounts of stored channel sediment. Re-mobilized historic sediment appears to increase suspended sediment load, and may be a significant, previously unrecognized sediment source. Thus, accurately mapping and quantifying channel deposits is a critical step for assessing sediment budgets, especially in Total Maximum Daily Load (TMDL) studies attempting to relate upslope management to suspended sediment production.

Introduction

The South Fork Noyo River is a major tributary of the Noyo River, which drains to the Pacific Ocean at the town of Fort Bragg in coastal Mendocino County, California *(fig. 1)*. The watershed has been heavily impacted by widespread clearcut logging over the last century. As a consequence, large volumes of sediment have been delivered to watercourses within the basin. Management practices conducted following the 1973 Forest Practice Act have contributed to a decrease in the rate of sediment delivery, although, large volumes of sediment continue to affect the ecology of the watershed (USEPA 1999). Historically, large populations of coho salmon and steelhead reproduced in the river (Brown and others 1994). Drastically declining fish

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populations over the past several decades (CDFG 1995a, 1995b) have raised concerns over the cumulative impacts of sediment on water quality, fish habitat, and the aquatic environment.

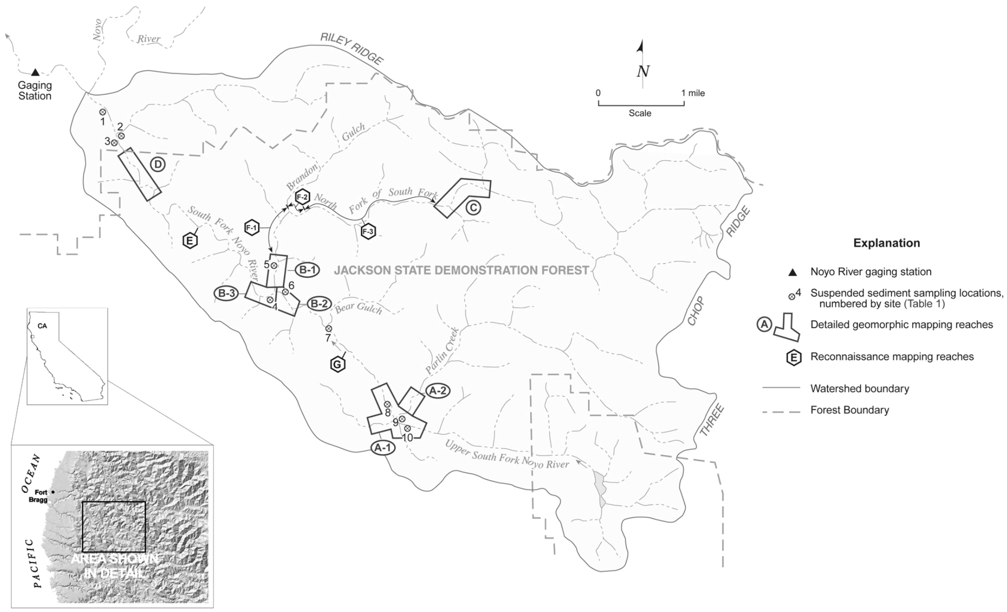

Figure 1—Drainage map of the South Fork Noyo River watershed showing detailed geomorphic mapping locations, reconnaissance mapping reaches, suspended sediment sampling locations, cross section locations, watershed boundary, and property boundary of Jackson State Demonstration Forest.

In response to these concerns, the Noyo River watershed was listed as a sediment impaired waterbody and included in the 1998 Section 303(d) list adopted by the State of California North Coast Regional Water Quality Control Board. In 1999, the Environmental Protection Agency (EPA) established the Noyo River TMDL for sediment, and identified sediment loading allocations aimed at improving water quality criteria for sediment. Accurately determining sediment loads for large watersheds is non-trivial, and office-based estimates are often associated with large uncertainties. The EPA acknowledges that large uncertainties in sediment input/storage estimates may be due to incompatibilities between field and office-based analyses (USEPA 1999). We believe that field-based sediment storage estimates are needed to improve office-based estimates. Thus, quantifying reasonable ranges of sediment input from, and storage in, these watershed sources is critical to understanding the sediment transport processes within the SFNR watershed, and to evaluating the long-term impacts of sediment transport within the SFNR ecological system.

The primary objectives of this assessment are to: (1) collect basic data on volumes of sediment stored and transported within the SFNR watershed over the past approximately 110 years, and (2) collect present-day stream flow and sediment transport data from the main stem SFNR and its major tributaries. These data provide information on long- and short-term storage and transport within the SFNR watershed and illustrate the importance of field-based information in sediment budget analyses.

Approach and Methods

We assessed the historic and current influences on channel morphology by conducting detailed geomorphic field mapping along four stream reaches (Areas A, B, C and D; *fig. 1*). Within these study reaches, we developed detailed geomorphic maps of current channel conditions showing the locations of fluvial terrace, gravel bar, and channel deposits. For field mapping, a string line painted at 25 foot intervals was tied tight along a straight line of sight in the channel thalweg. The compass bearing of the string line was plotted on the field map and tape and compass methods were used to map the dimensions of geomorphic units.

The field maps were converted into a Geographic Information System (GIS) format and used to calculate the area of all of the mapped deposits. These data were combined with field observations of deposit thickness to estimate the sediment volume for each deposit. Cumulative terrace and channel storage volume for each stream reach was calculated as a sum of individual terrace and channel deposits. Sediment thickness is the largest source of error in estimating storage volume.

Individual terrace and gravel bar deposit thickness was assumed to be the distance from the deepest scour in the active channel to the top of the surface. Field evidence used to determine the minimum thickness of channel storage included the depth of scour pools, depth measured at the downstream side of debris dams, the diameter of logs partially buried in the channel, and where available, the surface of bedrock. We infer that the estimates of the sediment volume associated with channel deposits represent minimum reasonable values. Additionally, because information usually is not available on the depth to bedrock beneath gravel bar or historic terrace deposits, we estimate thickness for these deposits as the sum of the sediment thickness estimated in the channel and the height of the respective surface. Because of this, estimates of the sediment volume associated with gravel bars and historic terraces combined represent minimum storage values associated with the active channel. In addition, sediment volume was quantified similarly in channel reaches between the detailed stream reaches (Areas E, F, and G; *fig. 1*), with the exception that surface area was estimated using pace measuring techniques.

To assess present-day hydrology and sediment transport within the major sub-watershed areas in the SFNR watershed, we established ten streamflow and suspended sediment sampling locations (numbered 1 to 10, *fig. 1*) and monitored these stations through WY2001. A standard staff plate and fence posts driven into the streambed were used to measure stream flow stage. Continuous stage recorders with pressure transducers were installed at four locations (Sites 1, 5, 9, and 10; *fig. 1*). Stream flow measurements were taken at all sites with a Price AA or Pygmy current meter and an AquaCalc 5000-Advanced Stream Flow Computer. Depth-integrated turbidity and suspended sediment sampling was performed at most locations. At locations where it was not possible to get a true depth-integrated sample, grab samples or modified depth-integrated samples were taken. The streamflow and sediment data were used to develop relations between stage, discharge, suspended sediment load, suspended sediment concentration, turbidity, and suspended sediment load per unit area (Koehler and others 2001). Total suspended sediment loads calculated for each sampling station were used to compare sediment loads between sub-watershed basins and to assess present-day sediment transport through the watershed.

Results

Locations and Amounts of Stored Sediment

Within each study area along the SFNR, we identified three distinct geologic map units, including deposits associated with pre-historic terraces, historic terraces, and the active channel *(fig. 2)*. Pre-historic terraces were identified by the presence of old-growth redwood stumps in growth position on the terrace surface. This map unit approximates the terrace configuration in the SFNR watershed prior to logging initiation in the late 1800s. Bedrock strath exposures along the channel margin indicate that the terraces are associated with three to eight feet of sediment, which probably is in permanent storage on the basis of deep incision (five to 20 feet). Historic terraces were delineated based on the presence of chainsawed logs within terrace deposits and an absence of old-growth stumps. Based on abundant logging debris only in historic terrace deposits, we infer that the historic terraces represent the maximum amount of channel aggradation that has occurred since the initiation of logging. Historic terraces are most common near the confluence of major tributaries *(fig. 1)*. The deposits associated with these terraces are approximately three to six feet thick. The terraces are a relatively constant height along the stream profile and are inset into pre-historic terraces and bedrock. Sediment stored in historic terrace deposits is subject to bank erosion but is trapped primarily in long-term storage.

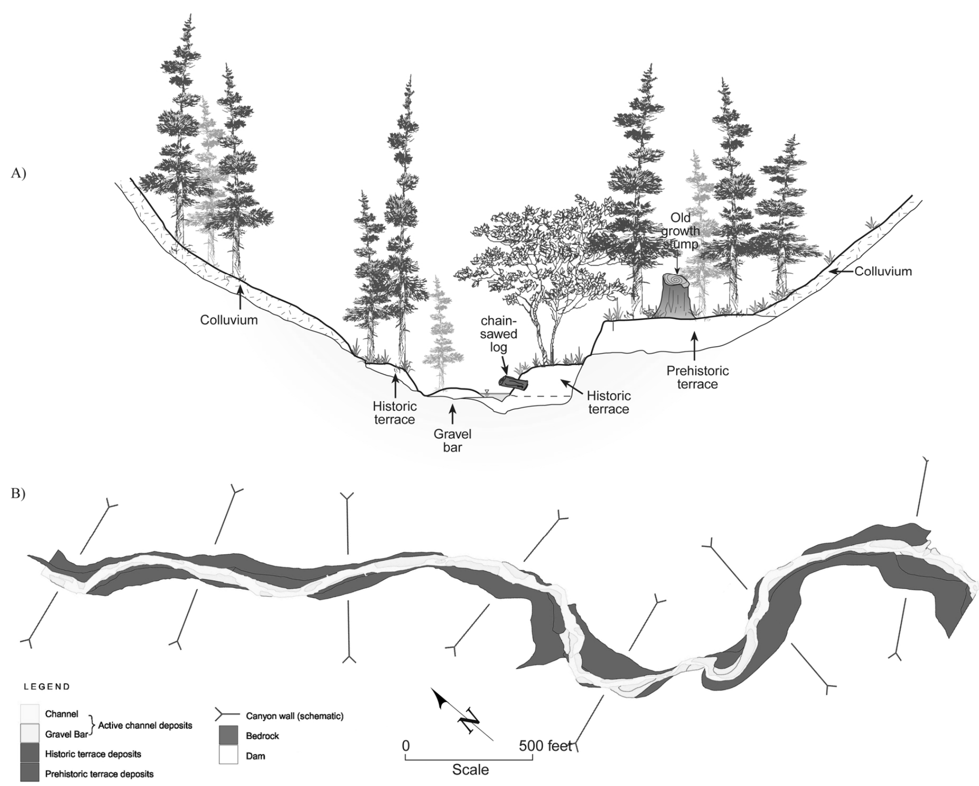

Figure 2—A) Schematic sketch of typical South Fork Noyo River channel showing valley margin, prehistoric terrace, historic terraces, gravel bar, and channel. Historic terrace deposits are observed on bedrock in some locations (left) and on channel deposits in other locations (right). Old growth redwood stumps are diagnostic of prehistoric deposits and embedded chain-sawed logs are diagnostic of historic deposits. Prehistoric terraces typically support second-growth redwood trees and ferns, historic terraces typically support alder trees and grasses. B) Detailed geologic map of mapping area D.

Active channel deposits exist throughout the study area, but are more extensive in downstream locations (Areas B, D, and E on *fig. 1*). These deposits are composed of both gravel bar and channel deposits. Channel deposits are submerged by the river throughout the year and range in thickness from approximately 0.5 to four feet, with occasional pockets as deep as 10 feet. Gravel bar deposits are submerged only during storm events, and range in thickness from approximately 0.5 to three feet. Based on the presence of chainsawed logs buried in the channel, we infer that the active channel deposits post-date the initiation of logging in the SFNR and represent transport of historic sediment.

Table 1 summarizes the total volume of each type of deposit within the detailed and reconnaissance mapping areas. Because individual mapping areas are different sizes, the total volume associated with each deposit in each stream reach is averaged over river distance for comparative purposes *(table 2)*. *Figure 3* shows active channel storage and historic terrace storage volumes for each stream reach. Map Areas A, F, and G have similar active channel storage (less than 13,300 yds^3/mile), whereas Areas B, C, D, and E have active channel storage of more than 20,000 yds^3/mile. Historic terrace sediment distribution is similar for areas D, E, F, and G (less than 5,000 yds^3/mile), however areas A, B, and C have considerably more stored historic terrace sediment *(table 3* and *fig. 3)*. Overall, the volume of sediment stored in the active channel is much more than the volume of the historic terrace deposits, with the exception of Area A. These data show that a large amount of the sediment in the SFNR watershed is stored along the main channel downstream of the North Fork of the SFNR. From these relations, we infer that there has been sufficient time since the logging operations and subsequent terrace deposition to erode the historic terrace deposits and redistribute this material downstream. We also infer that the combined volume of sediment stored in the active channel and historic terrace locations represents the minimum amount of material introduced to the South Fork Noyo river system by logging operations.

Table 3 shows the total post-logging sediment (in other words, active channel and historic terrace) remaining in the SFNR study area. The total post-logging sediment volume in storage over the entire study area is estimated at 225,000 yds^3 or approximately 22,000 yds^3/mile *(table 3)*. Areas F and G, which contain the least post-logging sediment, are located directly upstream of the confluence of the SFNR and the North Fork of the SFNR, and have bedrock exposed along much of their distance. The scarcity of historic terrace remnants and the low volume of active channel sediment within Areas F and G imply that much of the post-logging sediment has been transported downstream. This relationship may be related to the narrow confined valley (between pre-historic terraces) in Areas F and G and the comparatively wider valleys in Areas B, D, and E. Alternatively, the low sediment storage in Areas F and G may be related to a lesser amount of debris left by past logging operations. Notably, areas directly downstream from Areas F and G (in other words, Areas C and A, respectively) have considerably more post-logging sediment in storage than the stream reaches located directly upstream (Areas G and F, respectively). This probably is related to a wider channel in Area C, and a channel confluence in Area A.

Present-Day Hydrology WY2001

Streamflow measurements and sediment transport data included most of the significant storm events in WY2001, although few large storms provided relatively few opportunities to collect high-flow discharge measurements and sediment samples. One hundred and fifteen sediment transport measurements were made at the 10 sampling stations in WY2001 (Koehler and others 2001). *Table 4* shows the total suspended sediment load (tons) and the unit rate (tons/mi^2) for each sampling station, and *figure 3* shows the suspended sediment load distribution. Suspended sediment loads computed for each sampling station ranged from 14 tons at the mouth of Bear Gulch (Site 7, *fig. 1*) to 685 tons on the SFNR at the downstream end of the study area (Site 1, *fig. 1*). Total suspended sediment load increased downstream as the drainage area increased from Bear Gulch (Site 7) through the SFNR at Site 4. However, between this site and the mouth of Kass Creek suspended sediment load dramatically increased from 12.5 to 25.4 tons/mi^2, suggesting that a readily mobilized source of sediment exists within this stream reach. We infer that the source for this sediment is the large volume of sediment stored in the active channel that is remobilized during storm events.

Table 1—*Total volume of sediment stored in active channel deposits, historic terrace deposits, and pre-historic terrace deposits for each detailed mapping area (Area A-1 to Area D) and reconnaissance mapping area (Area E to Area G).*

Stream reach	River dist. (miles)	Active channel deposits (yds^3) *			Historic terrace deposits (yds^3) *	Pre-historic terrace deposits (yds^3) * ≠
		Gravel bar deposits (yds^3) *	Channel deposits (yds^3) Ø	Total active channel deposits (yds^3) *		
Area A-1	1	3,900	5,400	9,300	19,200	199,400
Area A-2	0.3	500	700	1,200	1,300	N.D. ∞
Area B-1	0.5	5,500	4,400	9,900	4,500	68,300
Area B-2	0.4	5,400	3,300	8,700	3,200	82,300
Area B-3	0.4	5,700	4,400	10,100	4,300	34,100
Area C	0.8	9,700	7,100	16,800	10,100	26,100
Area D	0.8	9,500	7,200	16,700	2,700	44,500
Area E	2.2	29,500	26,700	56,200	7,000	3,316,300
Area F-1	0.4	1,600	2,000	3,600	1,800	22,100
Area F-2	0.3	100	600	700	0	3,700
Area F-3	1.9	8,300	4,600	12,900	6,200	93,500
Area G	1.5	4,500	7,000	11,500	7,600	65,900
All areas	**10.27**	**84,200**	**73,400**	**157,600**	**67,900**	**3,956,200**

* Reported values represent minimum potential storage volume due to uncertainties in terrace thickness at the back edge of the deposit.

Ø Reported values represent minimum storage volume.

≠ Pre-historic terrace sediment volumes are based on an assumed 5 foot thickness except for Area A which is calculated based on 4 foot thickness determined from field observation. (Range of depth error is +/- 3 feet).

∞ N.D.; no data. Prehistoric terrace volume for Area A-2 is included in the volume calculated for A-1.

Table 2—*Sediment storage in active channel deposits, historic terrace deposits, and pre-historic terrace deposits averaged per river mile for each detailed mapping area (Area A-1 to Area D) and each reconnaissance mapping area (Area E to Area G).*

Stream reach	River dist. (miles)	Active channel deposits (yds^3/mile)*			Historic terrace deposits (yds^3/mile)*	Pre-historic terrace deposits (yds^3/mile)*
		Gravel bar storage (yds^3/mile)*	Summer channel storage (yds^3/mile)Ø	Total active channel storage (yds^3/mile)*		
Area A-1	1	3,900	5,400	9,300	19,200	199,400
Area A-2	0.3	1,600	2,300	4,000	4,300	N.D.∞
Area B-1	0.5	11,000	8,800	19,800	9,000	136,600
Area B-2	0.4	13,500	8,300	21,800	8,000	205,800
Area B-3	0.4	14,300	11,000	25,300	10,800	85,300
Area C	0.8	12,100	8,900	21,000	12,700	32,600
Area D	0.8	11,900	9,000	20,900	3,400	55,600
Area E	2.2	13,400	12,100	25,500	3,200	1,507,400
Area F-1	0.4	4,000	5,000	9,000	4,500	55,300
Area F-2	0.3	300	2,000	2,300	0	12,300
Area F-3	1.9	4,400	2,400	6,800	3,300	49,200
Area G	1.5	3,000	4,700	7,700	5,100	43,900
All Areas	**10.3**	**8,200**	**7,100**	**15,300**	**6,600**	**384,100**

* Reported values represent minimum potential storage volume due to uncertainties in terrace depth at the back edge of deposit.
Ø Reported values represent minimum storage volume.
∞ N.D.; no data, pre-historic terrace volume for Area A-2 is included in the volume calculated for A-1.

Table 3—*Total amount of post-logging sediment remaining in the South Fork Noyo River and tributaries by stream reach. The values represent the sum of sediment stored in the active channel and historic terrace deposits.*

Stream reach	River distance (miles)	Total volume of post-logging sediment (yds^3)*	Total volume of post-logging sediment averaged for river distance (yds^3/mi)*
Area A-1	1	28,500	28,500
Area A-2	0.3	2,500	8,300
Area B-1	0.5	14,400	28,800
Area B-2	0.4	11,900	29,800
Area B-3	0.4	14,400	36,000
Area C	0.8	26,900	33,600
Area D	0.8	19,400	24,200
Area E	2.2	63,200	28,700
Area F-1	0.4	5,400	13,500
Area F-2	0.3	700	2,300
Area F-3	1.9	19,100	10,100
Area G	1.5	19,100	12,700
All Areas	**10.3**	**225,500**	**21,900**

*Reported values represent minimum potential storage volume.

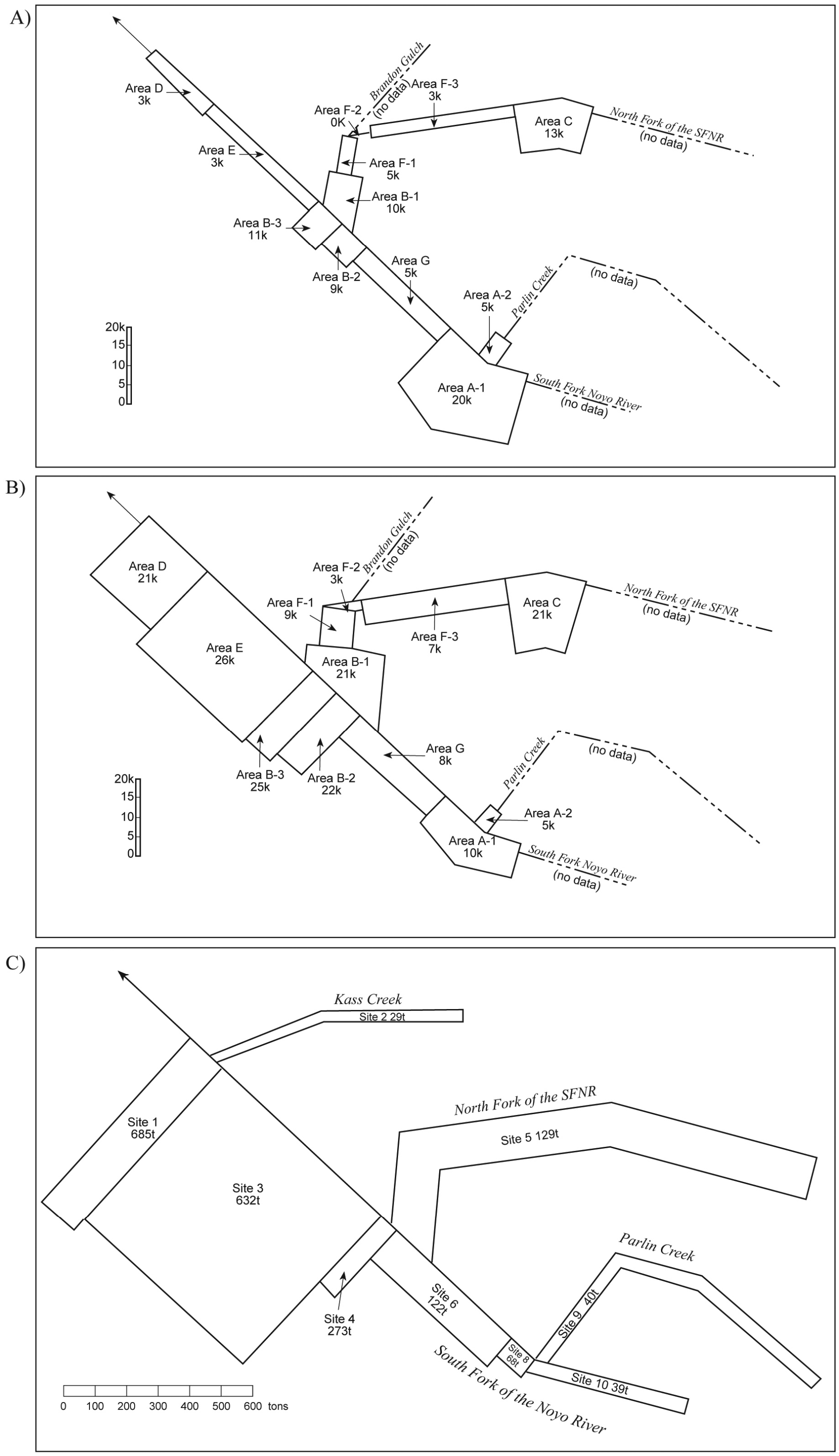

Figure 3—Schematic box diagrams of the South Fork Noyo River showing; A) total volume of historic terrace storage in yds^3/mile, B) total volume of active channel deposits in yds^3/mile, and C) total suspended sediment for each sampling station in tons.

Table 4—*WY 2001 total suspended sediment load (SSL) in tons and tons per square mile for each sampling station.*

Station Number	Area (mi^2)	SSL (tons)	Unit SSL ($tons/mi^2$)
1	27	685	25
2	2.21	29	13
3	25	632	25
4	22	273	13
5	9.9	129	13
6	12	122	10
7	1	14	13
8	9.2	68	7
9	4.4	40	9
10	3.7	39	11

Discussion

Our detailed channel mapping identified 158,000 yds^3 of sediment stored in the active channel and 68,000 yds^3 of sediment stored in historic terraces *(table 2)*. This sediment likely is mobilized during winter storm flows. The greatest amount of active channel storage occurs between Kass Creek and the mouth of the North Fork SFNR (Areas B, D, and E). In contrast to upstream areas, suspended sediment measured in this area showed a dramatic increase in the volume of sediment produced, where approximately 360 tons of suspended sediment were delivered from only 2.9 mi^2. Thus, the greatest amount of stored channel sediment is spatially coincident with the location of the largest amount of suspended sediment load *(fig. 3)*.

The source for this suspended sediment is most likely sediment stored in the active channel that is re-mobilized during storm events, rather than eroded from historic terrace deposits. The volume of sediment stored in historic terraces along this reach (Areas B, D, and E; *figs. 1* and *3*) is less than along reaches upstream, suggesting that suspended sediment eroded from historic terraces by bank erosion is a minor component of the total suspended sediment load. We interpret that other possible sources of suspended sediment load (in other words, landslides, road erosion) are minor contributors, based on scarcity of slides along the channel margin and adjacent side slopes, and the consistent road density in the area. Thus, land management practices probably do not cause the relatively high suspended sediment load in Areas B, D, and E.

Short-term sediment budgets, evaluated over decadal time scales, generally rely on the assessment of sediment inputs determined from inspection of multiple sets of aerial photographs and limited field observation. The office-based sediment budget approach for the Noyo River TMDL, which included the SFNR, states that fluvial-induced alluvial storage change is a relatively minor term in the overall sediment budget (USEPA 1999). However, the TMDL notes that the discrepancy between inputs and outputs in the Noyo River watershed may be a result of sediment input volume errors or time lags from sediment delivery to transport through the system. In contrast to previous assumptions, our sediment storage and transport study shows that the amount of sediment stored in the SFNR for various lengths of time has a major influence on the assessment of the present-day sediment transport and the short-term sediment budget.

The addition of suspended sediment eroded from active channel deposits to watercourses appears to result in a dramatic increase in the overall suspended sediment load. Areas that contain large amounts of sediment stored in active channels likely are large contributors to the suspended sediment measured during present-day high-discharge events. Therefore, this research has demonstrated that the amount of sediment in long-term storage is a significant contributor to short-term suspended sediment load. Clearly, a distinction must be made between the amount of sediment introduced to the system over the short-term and the amount of sediment re-introduced to the system from long-term channel storage locations.

Future field-based sediment budget analyses for watersheds in the North Coast will benefit from accurate mapping and quantification of channel deposits. An understanding of the volume and timing of sediment stored in the channel is necessary to relate upstream management practices to suspended sediment production and to evaluate cumulative effects. By not addressing long-term sediment storage and relying solely on present-day suspended sediment sampling, suspended sediment load entering the watercourse by modern management practices can be substantially over-estimated.

Conclusions

We assessed the volume of past and present sedimentation within the SFNR by quantifying the volume associated with pre-historic terraces, historic terraces, and the active channel in four detailed mapping reaches and three reconnaissance surveys. Additionally, we assessed present day streamflow and sediment transport throughout the SFNR watershed by establishing and monitoring a stream gauge network for WY 2001.

Total post-logging sediment volume (active channel and historic terrace) in storage over the entire study area is estimated at 225,000 yds^3 or approximately 22,000 yds^3/mile. Comparison of the volume associated with historic terraces and the volume associated with the active channel indicates that a large portion of the sediment originally deposited in historic terraces has been eroded and transported downstream. A significant portion of this sediment presently is stored in the lower SFNR channel between its confluence with the North Fork of the SFNR and the mouth of the SFNR.

Suspended sediment loads computed for each sampling station ranged from 14 to 685 tons. Overall, most sites produced sediment at a fairly consistent rate with discharge, although a large increase in sediment transport occurred between the mouth of the North Fork SFNR (Site 4) and the site upstream of Kass Creek (Site 3). This implies that significant sources of readily accessible sediment are located in this reach. This readily accessible sediment is most likely the active channel sediment stored in Areas B, D,and E.

The detailed maps and hydrologic data produced in this research provide a snap-shot of the distribution of stored sediment and present day sediment transport within SFNR. These data represent a baseline datum from which to monitor future channel recovery and assess the effects of upslope management practices. This research suggests that past logging practices contributed many thousands of cubic yards of sediment to channels in the SFNR watershed, and that the river has the ability to transport this material downstream. This research also demonstrates the need for an understanding of in-channel sediment storage and transport for relating upslope forest management practices to suspended sediment load.

Acknowledgments

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