WATERSHED CONDITION, TURBIDITY, AND IMPLICATIONS FOR ANADROMOUS SALMONIDS IN NORTH COASTAL CALIFORNIA STREAMS

A Report to the California
North Coast Regional Water Quality Control Board
5550 Skylane Boulevard
Santa Rosa, California 95403

Randy Klein, Hydrologist
Redwood National and State Parks

Dr. William Trush, River Ecologist
McBain and Trush, Arcata CA

Matthew Buffleben, P.E.
California Regional Water Quality Control Board
North Coast Region

May 21, 2008

ACKNOWLEDGEMENTS

Funding for this project was made available by Adona White, Water Quality Engineer, of the California North Coast Regional Water Quality Control Board, Santa Rosa, California, without which this project could not have been undertaken.

A large portion of the turbidity data assembled for this project was collected within Redwood National and State Parks (RNSP) on national and state park lands as part of RNSP's hydrologic monitoring program. We are grateful to both the National Park Service for supporting hydrologic monitoring and to California State Parks for protecting and providing access to old-growth redwood watersheds. Special thanks go to Stephen Fisher of Prairie Creek Redwoods State Park, who has come to our aid many times when nature wreaks havoc on our gaging stations.

In addition to the data sets collected by RNSP, much of the turbidity data used in this project was generously provided by Brett Harvey (US Forest Service Pacific Southwest Forest and Range Experiment Station, Redwood Sciences Laboratory, Arcata, CA), Jack Lewis (formerly with Redwood Sciences Laboratory), Rand Eads (formerly with Redwood Sciences Laboratory, presently with River Metrics, LLC, Lafayette, OR), and Clark Fenton (formerly with Salmon Forever, Arcata, CA). Additional data sets were kindly provided by Teri Jo Barber (River to Ridge, Westport, CA), Stephen Levesque and Kevin Faucher (Campbell Timber Co., Fort Bragg, CA), Peter Manka (former graduate student at Humboldt State University, Arcata, CA), and Rocco Fiori (California State Parks). Cort Pryor and Brooke Connell of Graham Matthews and Associates (Arcata office) also provided data collected under contract with both Redwood National and State Parks and Campbell Timber Co.

Jack Lewis also provided thoughtful reviews of drafts and advice on data analysis, including an important suggestion to summarize corrections made to raw turbidity data (Appendix A). Jack also performed the multiple regression analyses and provided some interpretations therefrom. Review comments were also provided by Mary Ann Madej (US Geological Survey) and Adona White (North Coast Regional Water Quality Control Board). Rocco Fiori (California State Parks) provided input on the SINMAP analysis as well as turbidity data. Valerie Sherron (North Coast Regional Water Quality Control Board) provided some analysis of turbidity data. We also thank Judy Wartella (RNSP) and Ryan Tietjen (formerly with California State Parks) for their invaluable and competent acquisition and preparation of GIS data and maps and Brian Powell (McBain and Trush, Inc., Arcata, CA) for support of data analysis and graphics.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

It is widely acknowledged that historically intensive human disturbances increased erosion and sediment delivery rates to extreme levels in the 1950s through the 1970s across the north coast, and are likely continuing to affect turbidity durations to some degree. A more controversial question is to what extent contemporary land use is affecting present-day erosion, sediment delivery and turbidity. Using turbidity exceedence levels to indicate watershed disturbance, we approached this question from several perspectives.

Part A of this report follows up and expands on an earlier analysis (Klein, 2003) for which turbidity data sets from only eight sites were available. In the present study, annual turbidity data sets were assembled from up to 28 continuous turbidity and stage recording stations located on small streams in the northcoast region from Del Norte County in the north to Mendocino County in the south. Data spanning three water years (WY2003-2005) were processed to calculate lengths of time turbidity was higher than several thresholds. Turbidity thresholds ranged from 25 (frequently cited in the salmonid literature as causing ill effects when exceeded) to 1000 FNU. Turbidity exceedence analyses, similar to conventional flow exceedence analyses, were also performed, allowing comparison of turbidity levels at various exceedence probabilities.

Watersheds draining to the monitoring stations included six (6) composed of old-growth redwood forest, eight (8) with older (legacy) harvest, and 14 actively managed watersheds with varying levels of recent and ongoing harvest. Turbidity at the 10% exceedence level (‘10% turbidity’) ranged from 3 to 116 FNU for WY2005 (the wettest of the three), translating to 1.7 to 65 days above 25 FNU.

Analyses of watershed physiographic and land use characteristics for basin areas upstream of each gaging station were performed, creating a set of both natural and anthropogenic variables that might affect turbidity for each watershed. Regression analyses were then used to identify the most important variables for explaining variations in turbidity duration (10% exceedence) among the study watersheds. Thirty (30) watershed variables analyzed, including 15 natural variables characterizing watershed size, steepness, slope stability, and rainfall intensity, and 15 anthropogenic variables characterizing road networks and timber harvesting.

Regression analyses showed the average annual rate of timber harvest (expressed as clearcut equivalent area) explained the greatest amount of variability in 10% turbidity exceedence Drainage area was also a significant explanatory variable for turbidity duration, but was secondary in importance to harvest rate. Expressions of road system characteristics had high multicollinearity with harvest rate due to the close functional relationship between these variables. Road variables were ultimately not included in explanatory models because harvest rate was a slightly better explanatory variable.

In another analysis, we grouped the streams by annual average harvest rate classes of ‘no harvest’, ‘lower harvest’, and ‘high harvest’ (0, greater than 0 but less than 1.5%, and greater than 1.5%, respectively) and compared average turbidities among each class. The zero harvest group averaged 13 FNU for the 10% turbidity, while the lower harvest group averaged 20 FNU (58% above the zero harvest group average) and the higher harvest group averaged 61 FNU (369% above the zero harvest group average), well above the stated limit of ‘20% above background’ in the North Coast Basin Plan of the North Coast Regional Water Board. Based on these analyses, average annual harvest rates greater than about 1.5% (representing a 67-year rotation cycle) should be avoided in North Coast watersheds, with the caveat that watershed-specific adjustments are possible based on more detailed analyses.

Part B of this report uses turbidity relationships to harvest rate to model potential effects on anadromous salmonids within a cumulative watershed effects (CWE) framework. To evaluate CWEs on anadromous salmonids and the stream ecosystem, annual turbidigraphs were produced from WY1991 through WY2005 at annual average harvest rates of 0% to 6% for an 8 mi^2 old second-growth watershed in North Coastal California. The turbidigraphs were very conservative in that they used the ‘Lower Bound Lines’ to estimate turbidity from discharge, rather than a line of best fit. Turbidity thresholds established at 10, 25, and 50 FNU were applied to assess chronic background, moderate, and severe stress to stream ecosystems in each water year. A simple model of smolt growth and survival-to-adult-return (SAR), as influenced by the annual turbidigraph, indicated the minimum supportable adult steelhead population size could be more than halved at the 2% average annual timber harvest rate compared to that supported by an old second-growth watershed.

PART A: TURBIDITY DURATION AND WATERSHED CHARACTERISTICS

Introduction

Erosion, Sedimentation, and Chronic Turbidity

Turbidity and suspended sediment concentrations in coastal northern California streams are widely recognized as high compared to many other regions, and the relative roles of both natural and anthropogenic factors affecting turbidity regimes have been controversial subjects for decades. By adding fine (suspendable) sediment over background levels to stream networks, certain land management activities can elevate turbidities and suspended sediment concentrations for extended periods, both during and between winter storms; this phenomenon is referred to as “chronic turbidity”. Monitoring of suspended sediment and turbidity has traditionally focused almost exclusively on stormflows, relatively brief periods when turbidities are very high. This is due in no small part to limitations inherent in manual sampling and the difficulties and expense of accessing remote sites. However, recent technological advances that allow automated recording of turbidity provide data sets that permit assessment of chronic turbidity in unprecedented detail.

Increased erosion and sedimentation from land management activities have long been an issue of concern with regard to the health and sustainability of aquatic ecosystems. Until recently, the primary issues of concern, at least in the Western US, have centered on stream channel geomorphic changes (bank erosion, aggradation, loss of channel complexity, etc.) and streambed textural changes (fine sediment filling pools and infiltrating the channel bed, fining of riffles, etc.); changes we can see and measure when we visit streams during low flow periods. Such parameters are commonly employed in long-term trend monitoring programs and, if properly designed, their measurement provides important data for assessing watershed conditions and processes.

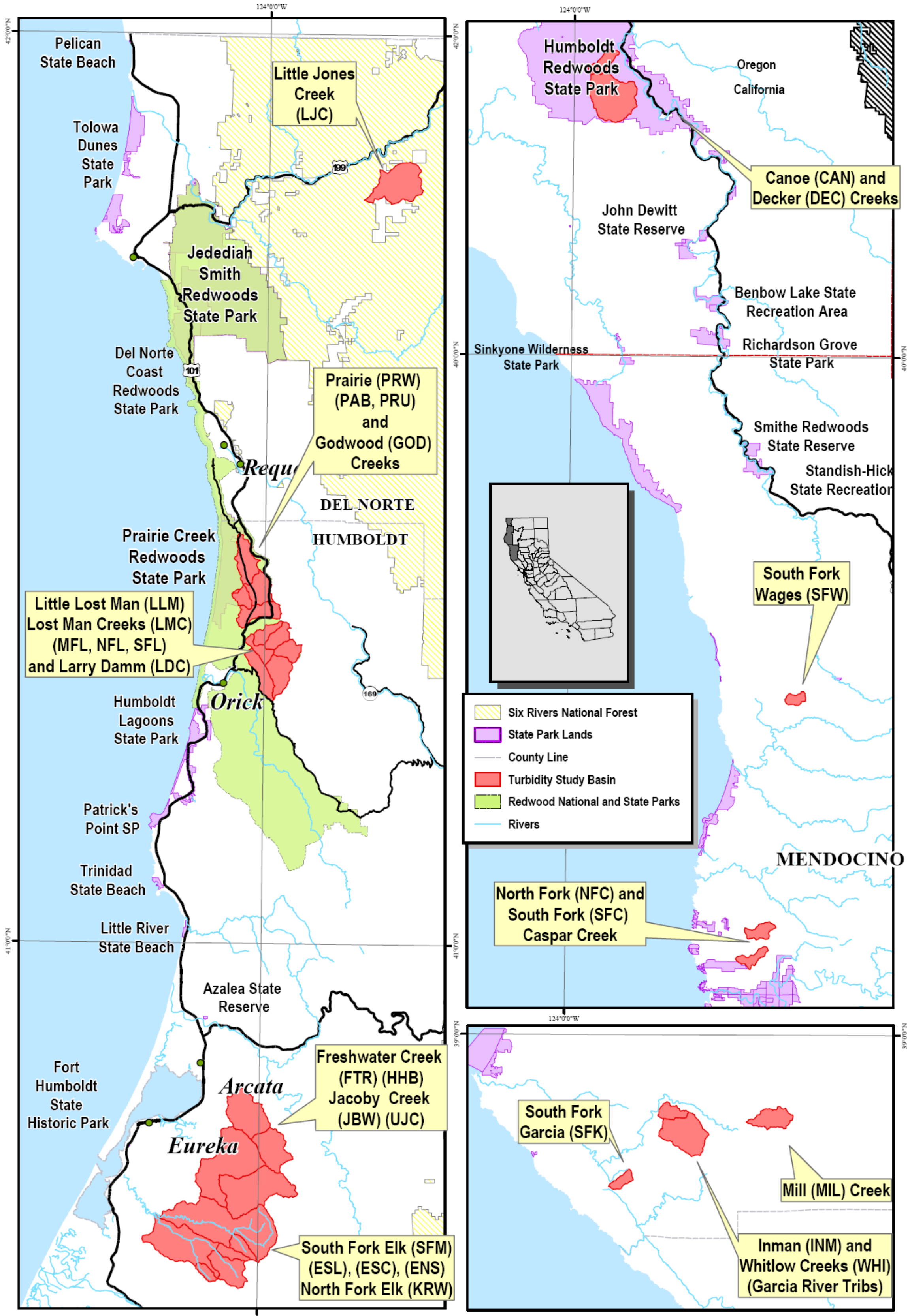
Much of the research into the effects of logging on erosion and sedimentation is heavily oriented toward the dramatic, i.e., large storms causing large inputs of sediment to channels, such as occurred during and after the infamous 1964 flood. Sediment budgets have been employed as an effective tool to quantify sediment inputs and the role of management. The yardstick by which the magnitude of effects is typically evaluated is the volumetric proportion of the sediment budget generated by a particular erosion process or resulting from a particular management practice.

Certainly, geomorphically large events are important determinants of the health of aquatic ecosystems and can have long-lasting effects, and the sediment budget is a fundamental tool for evaluating such events. However, less dramatic, but more chronic erosion and sedimentation processes (rainsplash and fluvial erosion and delivery of fine sediment from bare ground surfaces during small to moderate storms and continued transport between storms) are also important even though they may cumulatively represent a relatively small volume in a sediment budget compared to large storms.

Sediment budget studies in the north coast reveal that a large proportion of annual suspended sediment yield occurs during the typically few days when large stormflows occur. For example, Janda and others (1975) found that for Redwood Creek near Orick during water years 1971-73, flows exceeded only 5% of the time (5% exceedence flow) transported about 80% of the total suspended sediment load. By extension, sediment transport during the rest of the time (the other 95%) occurs at lower concentrations and may represent only 20% of the total load. However, we propose that it is an important component of sediment-derived chronic turbidity because of the longer duration, and thus may have disproportionately large effects on aquatic biota due to the extended duration of exposure. To protect and restore water quality and beneficial uses, land managers must first determine the extent to which human disturbance contributes to elevated sediment loads and the tendency for streams to experience extended periods of turbidity during the winter.

Study Streams

Figure 1 shows the 28 study watersheds. They span much of the geographical range of the north coast and capture much of the climatic, topographical, and geological variability therein.



/gis_maps/272_EPA_Turbidity_06/Final/Figure1_ LocationsofTurbidityStudyBasins.mxd 11.06

Figure 1. Location map of turbidity study basins.

Data Sources

Table 1 identifies the study basins and the entities that contributed their data (turbidity and GIS data) for this analysis.

Table 1. Data sources for turbidity study basins.

Stream (Code)	***River Basin***	***Turbidity Data Source****	***GIS Data Source(s)*****
Little Jones Cr (LJC)	Smith River	PSW	1,2,4
Upper Prairie Cr (PRU)	Redwood Creek	RNSP	1,2,3
Prairie Cr above Boyes (PAB)	Redwood Creek	RNSP	1,2,3
Godwood Cr (GOD)	Redwood Creek	RNSP	1,2,3
Prairie Cr above May (PRW)	Redwood Creek	RNSP	1,2,3
SF Lost Man Cr (SFL)	Redwood Creek	RNSP	1,2,3
Middle Fork Lost Man Cr (MFL)	Redwood Creek	RNSP	1,2,3
NF Lost Man Cr (NFL)	Redwood Creek	RNSP	1,2,3
Larry Damm Cr (LDC)	Redwood Creek	RNSP	1,2,3
Lost Man Creek (LMC)	Redwood Creek	RNSP	1,2,3
Little Lost Man Cr (LLM)	Redwood Creek	RNSP	1,2,3
Upper Jacoby Creek (UJC)	Humboldt Bay	PSW	1,2
Lower Jacoby Creek (JBW)	Humboldt Bay	R. Klein	1,2
Freshwater Creek at T. Roelofs (FTR)	Humboldt Bay	SF/WW	1,2
Freshwater Cr at Howard Heights Bridge (HHB)	Humboldt Bay	SF/WW	1,2
S Branch NF Elk R (ENS)	Humboldt Bay	PM/HSU	1,2
NF Elk R at K. Wrigley's (KRW)	Humboldt Bay	SF/WW	1,2
Corrigan Cr (ESC)	Humboldt Bay	PM/HSU	1,2
Little SF Elk R (ESL)	Humboldt Bay	PM/HSU	1,2
SF Elk R at M. Bohannon's (SFM)	Humboldt Bay	SF/WW	1,2
Canoe Creek (CAN)	Eel River	CSP	1,2
North Fork Caspar Creek (NFC)	Caspar Creek	USFS-PSW	1,2,4
South Fork Caspar Creek (SFC)	Caspar Creek	USFS-PSW	1,2,4
SF Wages Cr above Center Gulch (SFW)	Wages Creek	CTC	1,2
Inman Cr (INM)	Garcia River	T. Barber	1,2
Mill Cr (MIL)	Garcia River	T. Barber	1,2
Whitlow Cr (WHI)	Garcia River	T. Barber	1,2
SF Garcia R (SFK)	Garcia River	T. Barber	1,2

Turbidity Data Source Codes: **PSW**: US Forest Service, Pacific Southwest Forest and Range Experiment Station, Redwood Sciences Laboratory, Arcata, CA. **RNSP**: Redwood National and State Parks, Arcata, CA. **SF/WW**: Salmon Forever/Watershed Watch, Arcata, CA. **R. Klein**: Randy Klein, Arcata, CA. **PM/HSU**: Peter Manka/Humboldt State University. **CSP**: California State Parks. **CTC**: Campbell Timber Co. **T. Barber**: Terry Jo Barber, Westport, CA.

GIS Data Source Codes: 1: US Geological Survey. 2: California Department of Forestry and Fire Protection. 3: Redwood National and State Parks. 4: US Forest Service, Pacific Southwest Forest and Range Experiment Station, Redwood Sciences Laboratory, Arcata, CA

Watershed Characteristics

Table 2 lists physical information about watersheds draining to the 28 continuous turbidity monitoring sites used here. Drainage areas ranged from 1.1 to 28.1 square miles in size, with an average size of about 7 square miles. Most study basins have similar management, primarily timber harvest and associated activities (roading, yarding, etc.), although several also include some residential development and agricultural use (predominantly grazing). In addition, a number of the basins are relatively unmanaged, either having been logged in the distant past or left nearly pristine in national and state parklands. An anomaly among those is Canoe Creek, a mostly old-growth redwood basin in Humboldt Redwoods State Park, was extensively (73% of the total area) burned by wildfire in 2004.

To a lesser degree, Little Jones Creek also diverges from the other study basins, particularly in annual precipitation, slope steepness, geology, and elevation range. Among the 28 basins, only Little Jones Creek has substantial area that lies within the common snow zone (above about 3000 feet in elevation) that may cause it to exhibit runoff processes significantly influenced by snowmelt. Further, it is underlain by substantially different rock types (granitics) than the other watersheds (see Appendix D).

Table 2. Physical characteristics of turbidity study basins.

Stream	***Code***	***Drainage Area (mi^2)***	***Ave. Basin Slope (%)***	***Basin Relief (feet)[1]***	***Mean Annual prep. (in)[2]***
Canoe Creek	CAN	10.1	43	3200	105
S Branch NF Elk River	ENS	1.9	31	1700	55
Corrigan Creek	ESC	1.6	33	1300	55
Little South Fork Elk River	ESL	1.2	23	800	55
Freshwater Creek at Roelofs	FTR	12.8	38	2800	55
Godwood Creek	GOD	1.5	29	700	65
Freshwater Cr at HH Bridge	HHB	28.1	32	2200	55
Inman Creek (Garcia R Trib)	INM	7.5	43	1900	55
Lower Jacoby Creek	JBW	13.6	32	2100	55
North Fork Elk River	KRW	22.2	35	2300	55
Larry Damm Creek	LDC	1.8	26	1600	65
Little Jones Creek	LJC	8.6	51	3000	105
Little Lost Man Creek	LLM	3.5	29	2100	65
Lost Man Creek at Hatchery	LMC	12.1	30	1400	65
Middle Fork Lost Man Creek	MFL	2.3	36	1700	65
Mill Creek (Garcia R Trib)	MIL	3.6	39	1000	55
North Fork Caspar Creek	NFC	1.9	36	800	55
North Fork Lost Man Creek	NFL	2.2	34	1600	65
Prairie Cr above Boyes Cr	PAB	7.7	31	1400	65
Upper Prairie Creek	PRU	4.2	29	1300	65
Prairie Cr above May Cr	PRW	12.9	29	1800	65
South Fork Caspar Creek	SFC	1.6	33	1000	55
South Fork Garcia R	SFK	1.3	45	1900	55
South Fork Lost Man Creek	SFL	3.9	39	2000	65
South Fork Elk at M. Bohannon's	SFM	19.3	30	2000	55
SF Wages ab Center Gulch	SFW	1.1	58	1600	55
Upper Jacoby Creek	UJC	5.8	38	1600	55
Whitlow Creek (Garcia R Trib)	WHI	1.9	41	1400	55

[1] rounded to the nearest 100 feet

[2] from isohyetal maps at http "//frap.cdf.ca.gov/webdata/maps/statewide/rainmap.pdf"

Methods

Data Collection

Stream stage and turbidity data are recorded at the gaging stations using automated equipment. Data are typically recorded on 10- or 15-minute intervals (essentially continuous) using pressure transducers for stage and optical backscatter-type turbidity sensors. In most cases, gaging facilities include an electronic pumping water sampler that is controlled by the data logger to sample stormflows according to levels of and changes in turbidity (turbidity threshold sampling, or 'TTS', Eads and Lewis, 2002).

An increasing variety of turbidity sensors is available, each with unique optics and signal processing. The data assembled for this analysis were limited to just two sensor models: the OBS-3 sensor (formerly made by D&A Instruments Company, presently made by Campbell Scientific, Inc.) and the DTS-12 sensor (made by Forest Technology Systems, Inc.). [*Note: any mention of manufacturers and product names does not constitute endorsement by the federal government*].

The US Geological Survey (USGS) recently issued guidelines on turbidity measurement and reporting, available online at:

http://water.usgs.gov/owq/FieldManual/Chapter6/6.7_contents.html

Different turbidity units are assigned to different types of sensors based on the optical characteristics of each sensor. The data assembled for our analysis includes OBS-3 and DTS-12 data, with the latter being more common. For the OBS-3, the USGS assigns the units of formazin backscatter units, or 'FBU'. For the DTS-12, they assign units of formazin nephalometric units, or 'FNU'.

TTS station operation requires occasional discharge and stream stage measurements to develop discharge rating curves for estimating continuous discharges from recorded stages. For sites where it was available, discharge was used in our study to develop turbidity-discharge scatterplots.

Turbidity Data Processing

Raw turbidity data from the field was reviewed and corrected ('sanitized') as needed prior to being considered acceptable for analysis. Most of the data files provided by collecting entities for this analysis had already been corrected by their own protocols. However, only raw, uncorrected data were provided by some observers. In those cases, we performed data corrections. The correction process includes scanning the data record for suspect values and then either accepting or correcting the suspect values.

Typically, suspect turbidity values consist of two types: 1) gradually ascending values that reflect biofouling by algae growth on the turbidity sensor optics ('extended fouling'), and 2) abruptly rising values that result from either true spikes in turbidity or blockage of the sensing optics when leaf or other debris cling to the sensor housing ('instantaneous spikes').

The reviewer must first decide whether a suspect string of data is erroneous, and then if so, decide how to make corrections. Instantaneous spikes are the easiest to correct by simple linear interpolation between reliable values bounding the suspect value(s).

Extended fouling can also usually be corrected fairly reliably by subtracting gradually increasing value from the raw data over the period of fouling. When the sensor is cleaned on a field visit, the obvious sudden drop in turbidity indicates the amount by which the later data should be lowered. This adjustment factor becomes smaller as corrections are made backward through the record to the point where fouling began, as indicated by a gradual increase in turbidity readings during a non-storm period. Although there is judgment involved throughout the data correction process, these judgments are greatly aided by using the stage hydrograph, any sample data that may exist for the suspect period, and field notes from station visits that indicate sensor cleaning and other observations.

For missing data, records were either interpolated when only a few values were missing or were synthesized using the stage data and turbidity responses for storms of similar magnitude for longer periods of missing data. With few exceptions, only very small percentages of the records in any given file needed to be corrected or synthesized. Moreover, because the focus of this study was on chronic, low level (between-storm) turbidity, most results were negligibly influenced by corrections or additions made to the raw files. The data files, containing both raw and sanitized records, are provided in electronic form with this report. Appendix A lists each turbidity data file used in this report, the types of data quality issues encountered, the number of days affected by each issue type, and the method used to resolve the issue that led to an acceptable data file.

An important consideration in comparing turbidity data among different sites and time spans is to ensure that the data collected are compatible, either directly or by processing methods. Recent laboratory testing indicated that various in situ sensors give different turbidities for different sediments at various concentrations (Lewis and others, 2007). These differences are not trivial and vary depending on the types of sensors and sediments being compared. However, the data prepared by Lewis and others (2007) was used to develop conversion equations for transforming OBS-3 data to equivalent DTS-12 data. These equations (Table 3), were used to convert the OBS-3 turbidity data to equivalent DTS-12 values prior to turbidity duration analyses.

Because Canoe Creek was unique among the sites for which turbidity data were acquired in that it was heavily burned by wildfire just prior to turbidity data collection, it was not included in regression analyses. Canoe Creek OBS-3 data were, however, included in figures and tables displaying summary data, in which they are notated accordingly.

Table 3. Stream gaging stations with OBS-3 turbidity sensors and conversion equations used for estimating DTS-12 equivalent values.

Derived From:	Applied to OBS-3 data from:	Conversion Equation	R2
Upper Prairie Creek channel	PRU, GOD, PRW	$DTS = 1.0802 \times OBS^{1.0335}$	0.9987
Little Lost Man Creek channel, banks	LLM	$DTS = 0.8132 \times OBS^{1.0914}$	0.9988
Lower Jacoby Creek channel	UJC	$DTS = 0.9204 \times OBS^{1.0846}$	0.9986
Lower Freshwater Creek channel	FTR (2003 only)	$DTS = 0.9464 \times OBS^{1.0839}$	0.9985
NF Elk River channel	KRW (2003-04 only)	$DTS = 1.0729 \times OBS^{1.074}$	0.9994
SF Elk River channel	SFM (2003-04 only)	$DTS = 0.8914 \times OBS^{1.0935}$	0.9989
NF Caspar Creek channel	NFC, SFC	$DTS = 0.8173 \times OBS^{1.0976}$	0.9989

Turbidity Duration

Turbidity data were analyzed several simple ways for comparing turbidity duration characteristics among the study streams. Cumulative hours above several turbidity levels were calculated by sorting the records in descending order and tabulating hours. Turbidity levels used in the analyses as class breaks (e.g., 100, 200, 500 FNU) were somewhat arbitrary, although the lowest value (25 NTU) appears frequently in the scientific literature as a value above which measurable biological impacts occur. Higher class breaks separate increasingly larger turbidity levels to cover most of the range of observed values without utilizing an excessive number of classes.

In addition, a turbidity duration analysis similar to the customary flow (discharge) duration analysis was performed. The period used was December through the following May. This period was chosen because: 1) full year data files would have been substantially larger and more unwieldy for analysis and contain extended dry periods (summer/fall) when turbidity is zero, and 2) turbidity sensors are typically removed from the stream for summer low flow periods so they can be re-calibrated and are less vulnerable to vandalism, 3) many files did not contain turbidity data for the fall period, and 4) this period limited data analyses to that when turbidity is most likely to affect the freshwater life stages of anadromous salmonids.

Finally, results of the turbidity duration analyses were summarized by comparing turbidities at several turbidity exceedence probabilities: 0.1%, 1%, 2%, 5%, and 10%. Although the lower exceedence probabilities (e.g., 0.1%, 1%) include moderate to large stormflow conditions, the 10% exceedence probability extends the data to include lower stormflows and late recessional flows that better reflect chronic turbidity.

Watershed Characteristics

Geographical Information System (GIS) data were obtained from several sources (see Table 1) that provided elevation data (digital elevation models, or DEMs), stream lengths, roads, timber harvest and road construction going back through 1990, and other characteristics. From these data sets, several variables describing watershed characteristics were determined. The type of data available and the quality of that data varied among the data providers, and therefore the study basins. For example, road data across the area generally under-represent the true amount of roads on the landscape, although for some areas, it became evident that some road segments in the database did not actually exist (e.g., in Prairie Creek). Similarly, geological mapping varies within the northcoast in terms of the level of detail and whether or not mapping has been digitized, so we found it necessary to manually digitize a portion of the geologic mapping within the study area to complete the digital geology coverage. See Appendix B for further details on GIS data processing.

Another important caveat is that the timber harvest plan (THP) data used here represent harvest plan approval by CDF; there may be a time lag of up to three years, and in some rare case five years, between approval and implementation. Because we summed THP areas for five- to fifteen-year periods, inconsistencies between THP plan data and implementation were likely small. Finally, we note that some of the study watersheds are ‘nested’ (some larger gaged watersheds incorporate smaller gaged watersheds upstream), a common situation in hydrological analyses, but one that renders turbidity duration and watershed characteristics not strictly independent.

The watershed characteristics are separated into two categories; natural characteristics that serve as a background upon which the other category, anthropogenic influences, operates to create conditions that can elevate erosion and sediment delivery to streams, in turn elevating downstream turbidities. Table 4 lists the variables used in this analysis to explain variations in turbidity duration (the data can be found in Appendix C).

Table 4. Natural and anthropogenic explanatory variables evaluated for use in regression analyses to explain turbidity variations among study streams.

Natural Watershed Variables	***Units***	***Code***
Drainage Area	square miles	DRA
Average Watershed Slope	percent	AWS
Perrenial stream density	miles/square mile	PSD
Intermittent stream density	miles/square mile	ISD
Total stream density	miles/square mile	TSD
SINMAP area with FS < 1	percent of area	SIN<1
SINMAP area with FS 1.0-1.1	percent of area	SIN 1.0
SINMAP area with FS 1.1-1.2	percent of area	SIN 1.1
SINMAP area with FS >1.2	percent of area	SIN>1.2
Hypsometric Integral	n/a	HYP
Basin relief (elevation difference between headwaters and gage)	feet	RLF
WY2005 Annual Precipitation Recurrence Interval	years	ANP
WY2005 Maximum 1-day Precipitation Recurrence Interval	years	1DP
WY2005 Maximum 2-day Precipitation Recurrence Interval	years	2DP
WY2005 Maximum 3-day Precipitation Recurrence Interval	years	3DP
Basin-wide Road Characteristics	***Units***	***Code***
Basin-wide road density: all roads	miles/square mile	GRD
Basin-wide road density: lower slope roads	miles/square mile	LSRD
Basin-wide road density: mid-slope roads	miles/square mile	MSRD
Basin-wide road density: upper slope roads	miles/square mile	USRD
Anthropogenic Variables from THP Areas*	***Units***	***Code***
Clearcut equivalent area, 1990-2004 (0-15-yr preceding data)	weighted % of area	CCE 0-15
Clearcut equivalent area, 1995-2004 (0-10-yr preceding data)	weighted % of area	CCE 0-10
Clearcut equivalent area, 2000-2004 (0-5-yr preceding data)	weighted % of area	CCE 0-5
Clearcut equivalent area, 1995-1999 (5-10 yr predecing data)	weighted % of area	CCE 5-10
Clearcut equivalent area, 1990-1994 (10-15-yr preceding data)	weighted % of area	CCE 10-15
Tractor yarded area, 1990-2004 (15-yr)	percent of area	TYA-15
Permanent roads constructed 1990-2004 (15-yr)	miles/square mile	PRC-15
Seasonal roads constructed 1990-2004 (15-yr)	miles/square mile	SRC-15
Temporary roads constructed 1990-2004 (15-yr)	miles/square mile	TRC-15
Temporary and seasonal roads constructed 1990-2004 (15-yr)	miles/square mile	TSR-15
All non-paved roads constructed, 1990-2004 (15-yr)	miles/square mile	ARC-15

* THP data (road lengths, harvest and yarding areas) are expressed on a per-unit area basis for the entire gaged watershed; clearcut equivalent area (CCE) variables are expressed on an average annual basis.

Climate and geology are the most important categories of natural factors affecting turbidity. Geologic composition within the northcoast region contains a broad range of rock types and erosional sensitivities that undoubtedly affect turbidity regime (see Appendix D). However, no widely accepted classification system exists for evaluating erosional sensitivity, or susceptibility, as a function of bedrock type and other geological attributes. Alternatively, we used several potential surrogates for natural erosional sensitivity: 1) hypsometric integral (Strahler, 1952), 2) drainage density, and 3) slope stability model output using SINMAP.

Turbidity magnitude and duration will vary temporally and spatially with the amount of rainfall depths and intensities. To provide a climatic context for the turbidity data, data from north coast rainfall stations were assembled for the three water years analyzed (WY2003-2005). Recurrence interval (RI, years; e.g., ’25-year event’) was used as an index of erosive stress of the largest rainfall event recorded at the nearest long-term rainfall station to each study watershed. South Fork Caspar and Prairie creeks had long term rain gages that provided site-specific rainfall data. For the other sites, rainfall data from outside the study basins was used assuming it represented conditions within the watersheds. Recurrence intervals for observed rainfall at several time scales (annual, maximum 1-, 2-, and 3-day totals) were derived from rainfall frequency analyses provided for California stations online at:

http://www.climate.water.ca.gov/climate_data/

The recurrence intervals (RI, years) of observed rainfall were determined from the frequency analyses by interpolation.

Much research been conducted (on the north coast and elsewhere) on the roles of timber harvest, yarding, and road building on erosion, sediment delivery, sediment yield and water quality. Certainly other land uses affect turbidity in some locales, such as agriculture (row crops, vineyards, etc.) and rural residential development. However, because the streams included here drain watersheds where forest is the dominant land cover and timber production is the dominant land use, the majority of anthropogenic factors relate to timber harvest rates, silvicultural methods, and log transportation (skid trails, haul roads). The study streams include a number of relatively pristine streams that reside in parklands, as well as several that, although logged decades ago, have had little or no recent disturbance.

Harvest rate was a key explanatory variable in Klein (2003), where annual average harvest rates were computed using total acreages regardless of silvicultural methods. In the present analysis, variable erosion hazards due to silviculture (e.g., clearcutting, selection, thinning, etc.) were accounted for by multiplying acreages by factors that reflect the relative disturbance levels of the silvicultures employed. Adjustment factors in North Coast Regional Water Quality Control Board Order No. R1-2006-0039 (North Coast Regional Water Quality Control Board, 2006), were used, where each clearcut, right-of-way, and rehabilitation cut acre was accounted for on a one-to-one basis but acreages with lighter silvicultural methods were reduced by the factors given (e.g., 0.75 for shelterwood and seed tree removal, 0.5 for selection, commercial thin, etc.). All silvicultural practices and adjustment factors are shown in Table 5 below. Because adjustment factors for several silvicultural types were not included in the Regional Board's analysis, they were assigned factors based on an assumed level of disturbance relative to clearcutting. These are indicated by *italics* in Table 5. Of the types that were not assigned factors by the Regional Board, only "No Harvest Area" (NHRV) represented substantial acreage among the study watesheds.

Table 5. Silvicultural area adjustment factors.

Silviculture Type and GIS Code	**Adjustment Factor**
CLCT = Clearcut	1.00
CMTH = Commercial Thin	0.50
GSLN = Group Selection	0.50
REHB = Rehabilitation of Understocked Areas	1.00
ROAD = Road Right of Way	1.00
SASV = Sanitation Salvage	0.75
SHPC = Shelterwood Preparation Cut	0.75
SHRC = Shelterwood Removal Cut	0.75
SHSC = Shelterwood Seed Cut	0.75
SLCN = Selection	0.50
STRC = Seed Tree Removal Cut	0.75
STSC = Seed Tree Seed Cut	0.75
ALPR = Alternative Prescription	*0.75*
NHRV = No Harvest Area	*0.00*
OUT = Not Part of THP	*0.00*
TRAN = Transition	*0.25*
VRTN = Variable Retention	*0.50*

Multiple regression analyses were done using “R” (R Development Core Team, 2007) to explain the variability in turbidity duration among the study streams using the variables in Table 4. WY2005 was selected for the regression analysis because it had the greatest number of streams for which turbidity data were assembled. Regression analyses were conducted on two sets of data: one with all 27 streams (excluding Canoe Creek because of the wildfire) and a subset just including streams in Humboldt County (also excluding Canoe Creek). Obviously county boundaries don’t exert control over turbidity, but the considerable distances separating the Humboldt County streams from those in Mendocino and Del Norte counties accompany substantial differences in physiographic attributes such as rock type and tectonic uplift rates that must strongly affect turbidity regimes. The difficulty in quantitatively accounting for these differences was an analytical weakness that was reduced by performing a separate analysis that only included Humboldt County streams.

Correlation matrices (Appendix E) were produced to screen and limit the number of explanatory (X) variables for the multiple regression analyses. First we sorted the X variables into the following categories:

- Landform
- Watershed Size
- Harvesting
- Roads
- Rainfall

and then started with a basic model that included just the highest correlate with the Y variable (10%TU) from each category. Then we added up to 1 variable from each category if it significantly improved the model. Our primary diagnostic for evaluating model improvement was Akaike's Information Criterion (AIC) (Burnham and Anderson, 2002; Sakamoto and others, 1986), but we also examined other diagnostic criteria (residual mean standard error, adjusted R-squared, F-statistic, p-value). Within each of the two data sets (all 27 streams and the Humboldt County subset), we considered the best model to be the one that minimized the AIC.

Additional Turbidity Analyses

Several additional analyses of turbidity data were performed for the purposes of: 1) investigating possible alternative uses for turbidity rating curves, where discharge is a predictor of turbidity, and 2) evaluating possible effects of chronic turbidity on juvenile salmonids to link land use to fish sustainability.

Turbidity-discharge Relationships

We created scatterplots of discharge versus turbidity using WY2005 data from a subset of study streams that represented the range of watershed sizes and land use intensities of the full set. To accomplish this, we first devised a screening procedure to reduce the data set to a manageable size for plotting (at the 10-minute recording interval, the data set from Dec. to May, a period of 182 days, contains over 26,000 turbidity observations, which was overly cumbersome to work with). The procedure used was simply to extract only the observations taken at the top of each hour of the study period (about 4,400 observations) and then further reduced the number of data points by retaining only the 1550 observations having the highest turbidities. This resulted in a data subset that spanned nearly the full range of the complete set.

With this subset of turbidity observations, scatterplots were plotted with discharge (cfs per square mile) on the x-axis and turbidity (FNU) on the y-axis. Linear regression (least squares) was used to fit central tendency lines to the data set for each stream, specifying a y-intercept of zero. Although other mathematical functions (e.g., polynomial, logarithmic, exponential, etc.) might yield better fits, simple linear regression was used to allow comparison of slopes among the rating curves, with steeper slopes indicating greater turbidity at a specific discharge.

Another use of turbidity rating curves presented itself upon plotting the data: a sharply-defined bottom edge was observed in all the plots of reduced continuous turbidity data, and the slope of a line bounding the lower edge varied among sites. We visually fit lines to the lower edge of plotted points (which we termed ‘Lower Bound Line’ LBL) to determine if the slope was related to watershed variables correlated with the 10% turbidity exceedence listed in Table 4. As with linear regression, a steeper LBL would indicate a greater turbidity at a specified discharge, but limited to the minimum turbidity-discharge relationship for a site in this case. Hydrologically, the data points forming the LBL represent recessional stormflows when turbidity is typically much lower for a specific discharge than on rising limbs, thus using the LBL as a rating curve will result in a very conservative estimate of turbidity durations, as is the case in Part B.

Like the LBL slope, the y-intercept of the LBL appeared to vary systematically among the scatterplots, with lower (negative) intercepts associated with more turbid streams. The cleaner streams had higher y-intercepts, indicating that at lower recessional flows, there was lower (possibly zero) turbidity compared to more turbid streams. To keep the analysis as simple as possible, we chose to ignore the y-intercept for the time being.

We also investigated whether this Lower Bound Line varied with the hydrologic severity of a particular runoff season, which, if so, would limit its utility as a diagnostic criterion for watershed disturbance. We selected two of the sites (Upper Prairie Creek, PRU, and Upper Jacoby Creek, UJC) because continuous turbidity records for both spanned WY2001-2005 (five years) during which hydrologic conditions varied substantially. Lower Bound Line slopes were calculated for each year and evaluated across years.

Finally, we developed a suite of simplified turbidity rating curves from the relationships between annual average harvest rates and slope of the Lower Bound Line. As described above, this was an extremely conservative method for estimating turbidity from discharge. These curves were then used in the biological modeling portion of the analysis to relate timber harvest rate to salmonid run sustainability (Part B).

Results

Turbidity Duration

Data files with continuous turbidity (both raw, where possible, and corrected) and stage (and/or discharge, where possible) data have been compiled on compact disc (CD) for all available data files under separate cover. Appendix A summarizes turbidity data corrections for files analyzed (several files did not come with raw data, so no assessment of corrections was possible).

Table 6 summarizes the continuous data in the form of turbidity durations (hours above selected turbidity levels) and turbidity exceedences (% of time above a given turbidity level) for the study streams for WY2003-2005. The sites in Table 6 are ordered by decreasing turbidity at the 10% exceedence level. Figures 2-7 show these data graphically. Although we have included data for Canoe Creek in Table 6 and Figures 2-7, note that these data are in FBU rather than FNU like the others, and consequently are not comparable. Because there was no reliable means to convert the OBS-3 FBU data from this site to DTS-12 FNU equivalent values, it was dropped from further analyses.

Turbidities at the 10% exceedence probability ranged from 3 to 116 FNU. Similarly large ranges are spanned at other exceedence probabilities. Perhaps more tangible to many readers is the cumulative time above given turbidity levels. In two cases (**SFM**, or South Fork Elk River at M. Bohannon's, and **KRW**, North Fork Elk River, both Humboldt Bay tributaries) exceeded 25 FNU for over 1800 hours in WY2004. Moreover, both the Elk River and Freshwater Creek sites were consistently among the most turbid across all water years, with the exception of the Little South Fork Elk River, a near-pristine stream in the Headwaters Preserve. Both Upper and Lower Jacoby creeks (**UJC** and **JBW**, respectively) were also relatively turbid.

In contrast, some streams were exceptionally clear, with several never exceeding 100 FNU in WY2005 (**PRU**: Upper Prairie Creek; **LJC**: Little Jones Creek; **GOD**: Godwood Creek; and **SFW**: South Fork Wages Creek) and only rarely in other years. While Upper Prairie and Godwood creeks are near-pristine watersheds located within parklands, Little Jones and South Fork Wages creeks were logged decades ago. There is also a middle ground between the very turbid and very clear, those exhibiting 10% turbidities between about 20 and 40 FNU. These included older second-growth streams with no recent harvest in Humboldt County and several streams with ongoing harvest in Mendocino County.

Table 6. Turbidity duration hours and turbidity levels (FNU from 10-minute readings) at various exceedence probabilities for study basins, water years 2003-05.

WY2003 (n = 12)

	Turbidity at Specified Exceedence (FNU)					Cum. Hours Above Specified Turbidity					
Site/Year	**0.10**	**1.0**	**2**	**5**	**10**	**1000**	**500**	**200**	**100**	**50**	**25**
KRW03	1027	530	376	176	95	4.7	54.3	194.3	397.7	839.1	1569.9
JTG03	1102	531	366	156	82	6.8	49.7	173.0	352.0	709.3	1359.1
FTR03	870	449	312	138	75	1.0	34.0	145.3	312.3	727.6	1621.8
UJC03	679	229	149	71	37	1.2	9.2	55.5	143.2	321.0	729.5
LMC03	1566	690	333	94	37	15.8	59.7	129.5	209.0	344.2	590.0
NFC03	145	82	65	42	30	0.0	0.0	0.7	23.8	148.7	621.1
SFC03	172	91	68	40	30	0.0	0.0	0.8	32.0	139.3	591.1
SFL03	563	164	104	49	26	0.0	6.2	32.8	93.3	208.8	447.5
LLM03	289	99	55	20	8	0.0	0.5	16.2	42.0	95.8	179.3
PRU03	72	28	17	9	5	0.0	0.0	0.0	1.3	10.0	52.2
GOD04	74	25	16	7	5	0.0	0.0	0.0	3.0	14.5	43.5
LJC03	193	59	28	7	3	0.0	0.0	3.3	20.5	54.0	92.2

WY2004 (n = 25)

	Turbidity at Specified Exceedence (FNU)					Cum. Hours Above Specified Turbidity					
Site/Year	**0.10**	**1.0**	**2**	**5**	**10**	**1000**	**500**	**200**	**100**	**50**	**25**
SFM04	1066	474	347	171	93	5.3	39.3	188.7	403.3	945.6	1834.1
KRW04	706	393	289	164	87	0.0	23.5	176.0	356.7	999.8	1874.6
CAN04	*1037*	*501*	*319*	*133*	*60*	*4.8*	*44.3*	*148.0*	*280.0*	*523.1*	*1071.0*
ENS04	1178	397	272	109	47	8.3	26.7	129.2	231.8	411.8	930.8
FTR04	593	283	177	81	43	0.0	10.3	74.2	167.3	362.5	934.5
JBW04	650	254	181	85	43	0.0	9.0	75.3	187.0	379.5	701.3
ESC04	536	178	129	61	34	0.0	6.5	34.8	123.2	271.3	728.0
LDC04	888	197	113	47	25	2.2	15.5	43.2	102.3	206.3	424.3
SFC04	210	68	50	34	25	0.0	0.0	4.8	17.8	87.3	427.5
WHI04	539	200	101	41	25	1.2	6.3	44.0	88.5	179.3	416.8
NFC04	166	63	49	34	24	0.0	0.0	0.0	14.2	82.0	407.3
MFL04	423	159	94	42	21	0.0	2.2	31.7	81.3	188.8	372.2
UJC04	535	154	106	40	20	0.0	4.7	24.3	93.2	177.3	335.8
LMC04	817	260	125	44	20	1.3	13.3	58.5	103.5	194.8	349.5
NFL04	631	131	81	38	20	0.0	5.8	23.2	65.0	160.2	332.8
MIL04	472	148	78	35	20	0.0	3.2	29.3	68.0	142.2	316.0
SFL04	472	159	79	31	14	1.3	3.8	28.3	72.3	139.3	246.0
PRU04	82	25	18	13	11	0.0	0.0	0.0	2.8	11.0	43.3
ESL04	59	26	19	14	9	0.0	0.0	0.0	0.0	9.8	44.7
PRW04	236	51	30	14	8	0.0	0.0	5.7	19.8	44.8	113.5
SFW04	74	54	27	10	6	0.0	0.0	0.0	0.0	52.5	91.3
PAB04	178	30	18	8	5	0.0	0.0	2.8	10.8	27.8	59.7
LLM04	144	34	19	9	4	0.0	0.0	2.5	7.8	25.7	66.5
GOD04	82	15	11	5	3	0.0	0.0	0.5	2.5	7.5	24.5
LJC04	83	27	15	6	3	0.0	0.0	0.0	3.2	11.2	47.0

Table 6 (cont.')

WY2005 (n = 28)										
	Turbidity at Specified Exceedence (FNU)					**Cum. Hours Above Specified Turbidity**				
Site/Year	**0.10**	**1.0**	**2**	**5**	**10**	**1000**	**500**	**200**	**100**	**50**	**25**
SFM05	1245	551	370	185	116	11.3	54.3	195.3	512.8	936.3	1565.6
KRW05	766	376	271	161	93	1.3	25.2	157.2	399.0	809.8	1538.3
ENS05	1416	483	303	144	76	13.2	41.3	150.2	319.7	677.6	1290.1
HHB05	620	281	197	107	67	1.2	8.5	84.8	238.2	669.8	1413.5
FTR05	675	254	167	87	57	0.5	7.8	66.7	183.8	550.5	1363.1
CAN05	*509*	*225*	*152*	*92*	*56*	*0.0*	*5.7*	*56.0*	*185.7*	*484.7*	*936.0*
JBW05	794	307	205	96	53	0.7	14.2	89.7	211.0	469.8	1016.5
ESC05	785	249	148	78	50	0.8	13.7	56.3	140.3	439.8	1057.8
UJC05	1662	293	167	75	42	7.7	23.3	71.0	149.8	349.3	859.6
SFC05	258	110	77	48	37	0.0	0.0	10.5	51.8	197.0	909.3
NFC05	359	107	65	43	33	0.0	0.0	16.7	46.2	173.8	828.6
WHI05	416	149	92	48	29	0.5	2.0	26.3	78.3	208.8	551.8
INM05	327	127	64	40	26	0.0	0.3	24.2	53.3	138.3	503.6
SFL05	548	197	107	42	22	0.0	7.2	42.7	93.7	187.3	387.5
MFL05	590	157	87	40	21	0.0	7.7	32.3	75.7	172.5	379.3
LMC05	494	131	72	33	18	0.2	4.0	27.0	61.7	136.3	317.3
MIL05	235	99	73	34	18	0.0	0.0	5.7	43.2	140.5	308.3
NFL05	343	145	79	36	18	0.0	0.0	29.0	67.0	150.2	322.3
LDC05	213	106	66	31	16	0.0	0.0	6.8	47.8	120.2	278.3
LLM05	256	77	47	26	16	0.0	0.0	11.0	32.5	78.0	226.7
PRW05	290	94	55	26	14	0.0	0.0	11.3	38.3	98.0	228.8
ESL05	79	31	22	16	12	0.0	0.0	0.0	1.7	14.8	71.0
SFK05	259	71	45	20	11	0.0	0.0	9.7	23.8	76.0	179.8
PRU05	81	26	17	10	6	0.0	0.0	0.0	1.3	16.0	45.5
GOD05	66	23	16	9	6	0.0	0.0	0.0	0.0	12.5	34.3
LJC05	41	25	14	8	5	0.0	0.0	0.0	0.0	0.0	45.8
SFW05	60	15	10	6	4	0.0	0.0	0.0	0.0	7.0	15.5
PAB05	82	24	14	6	3	0.0	0.0	0.0	1.5	14.5	41.2

(note: sites appear in order of decreasing turbidity at the 10% exceedence level; italicized values represent unconverted OBS-3 data in FBU, or formazin backscatter units; site JTG was moved downstream after WY2003, and was re-named JBW)

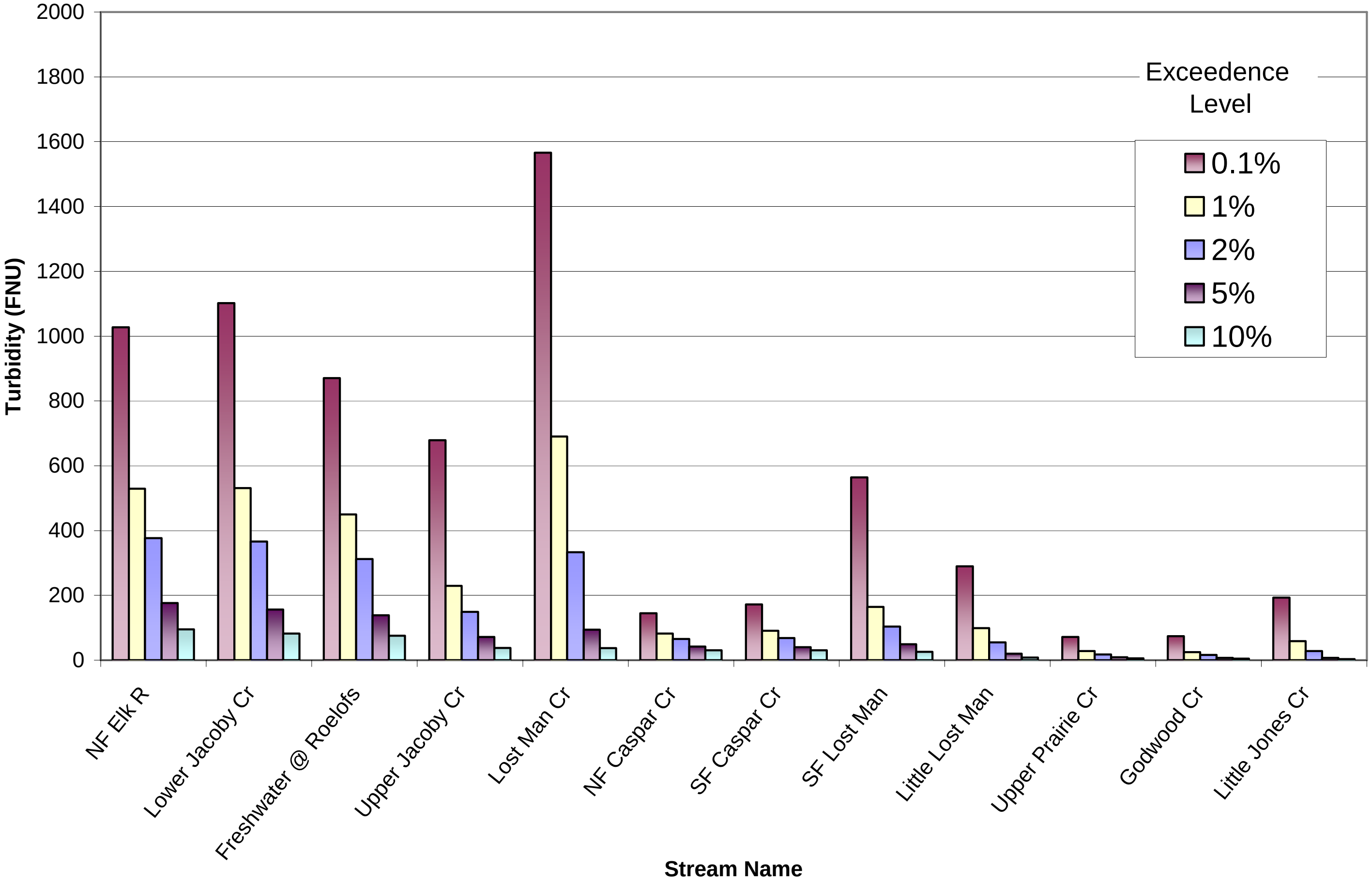


Figure 2. Turbidity exceedences for WY2003.

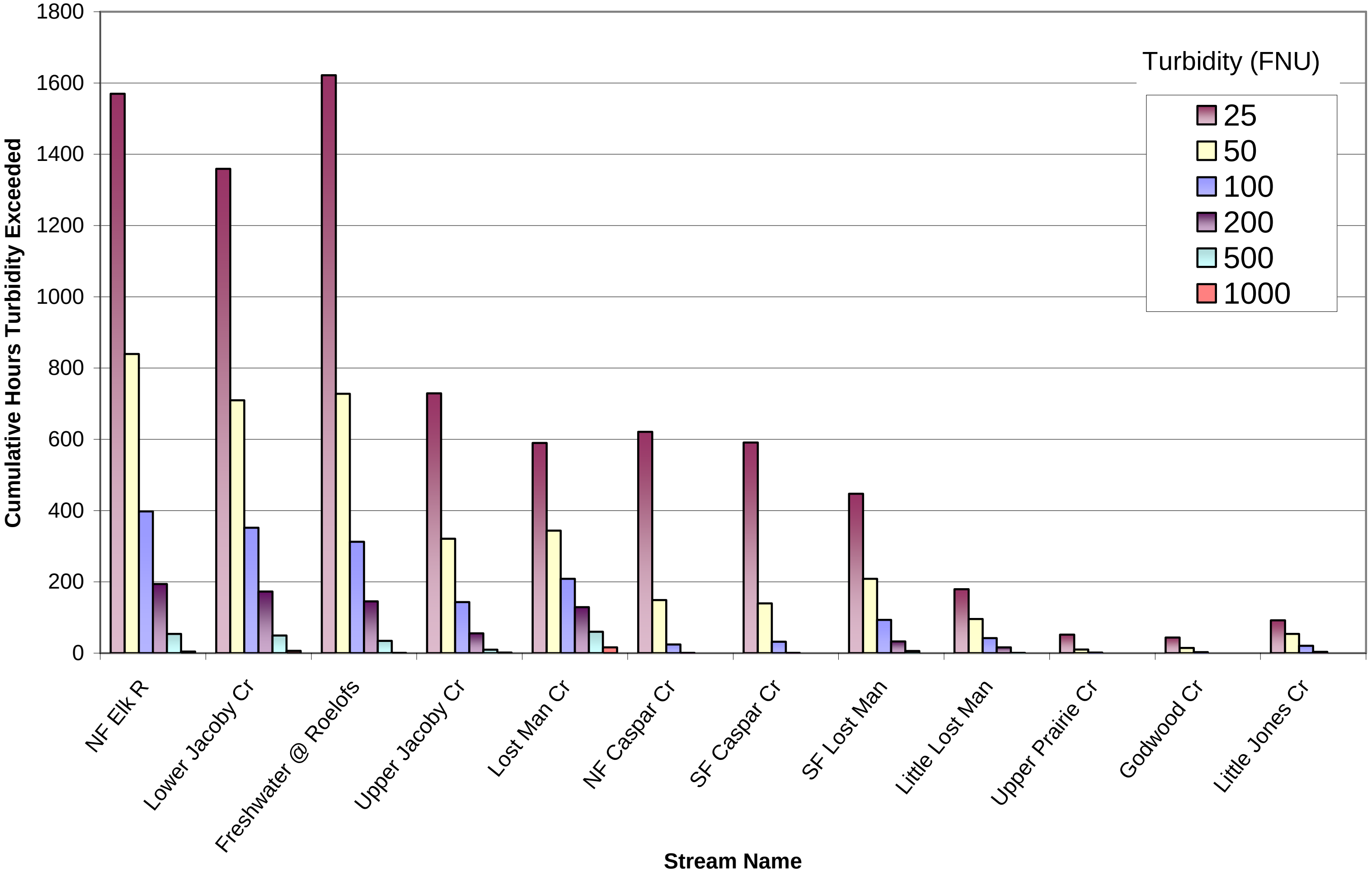


Figure 3. Turbidity durations for WY2003.

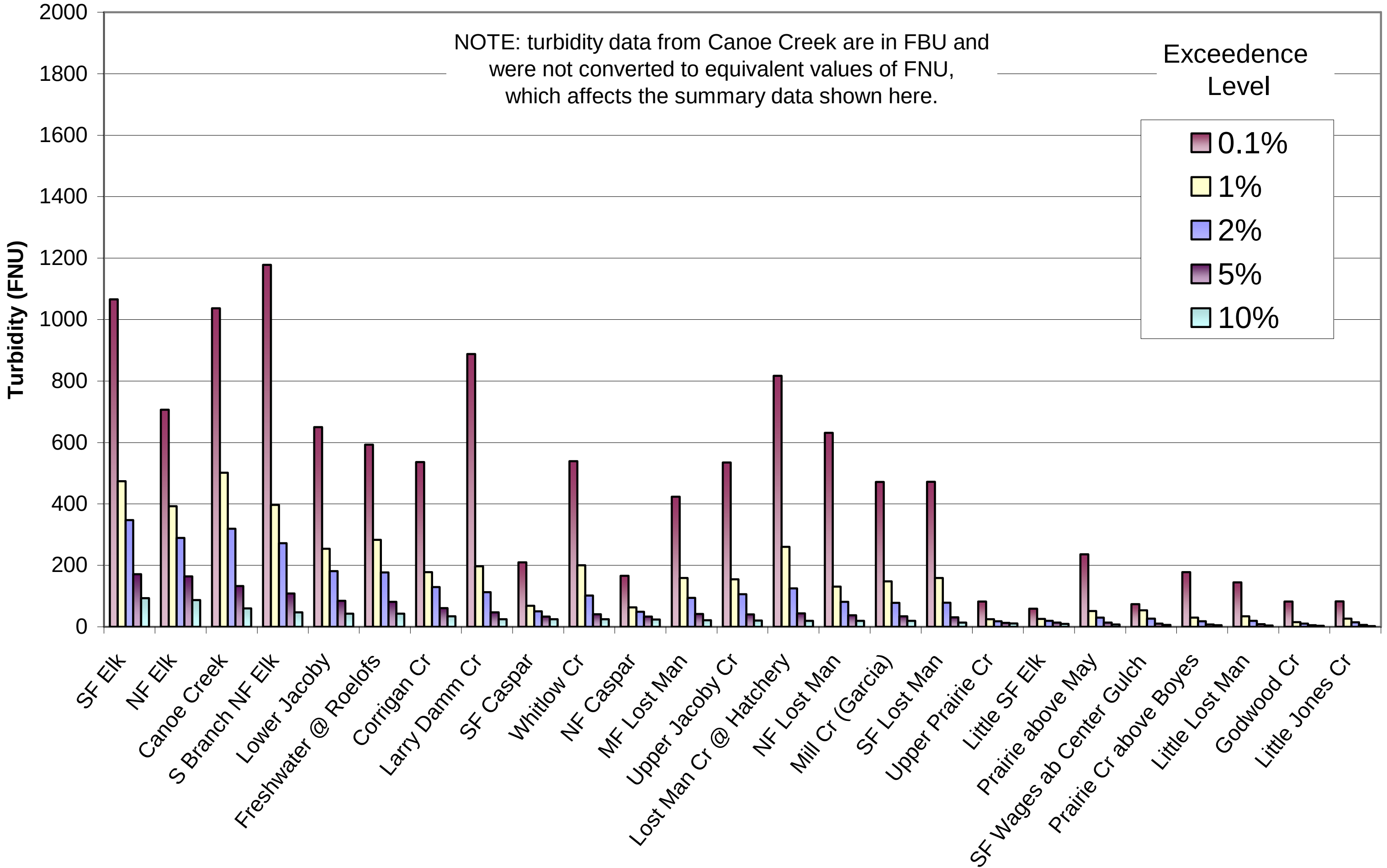


Figure 4. Turbidity exceedences for WY2004.

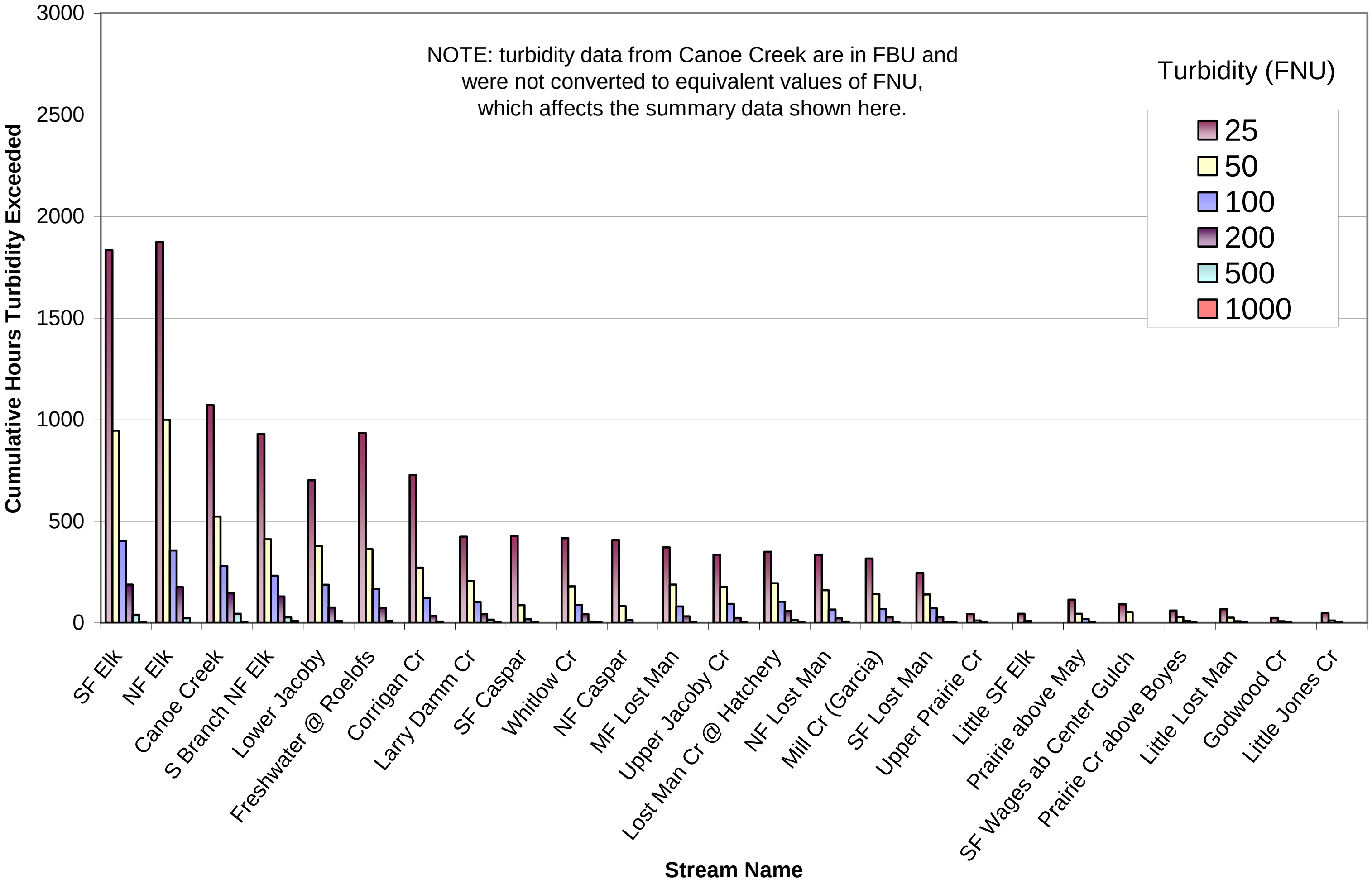


Figure 5. Turbidity durations for WY2004.

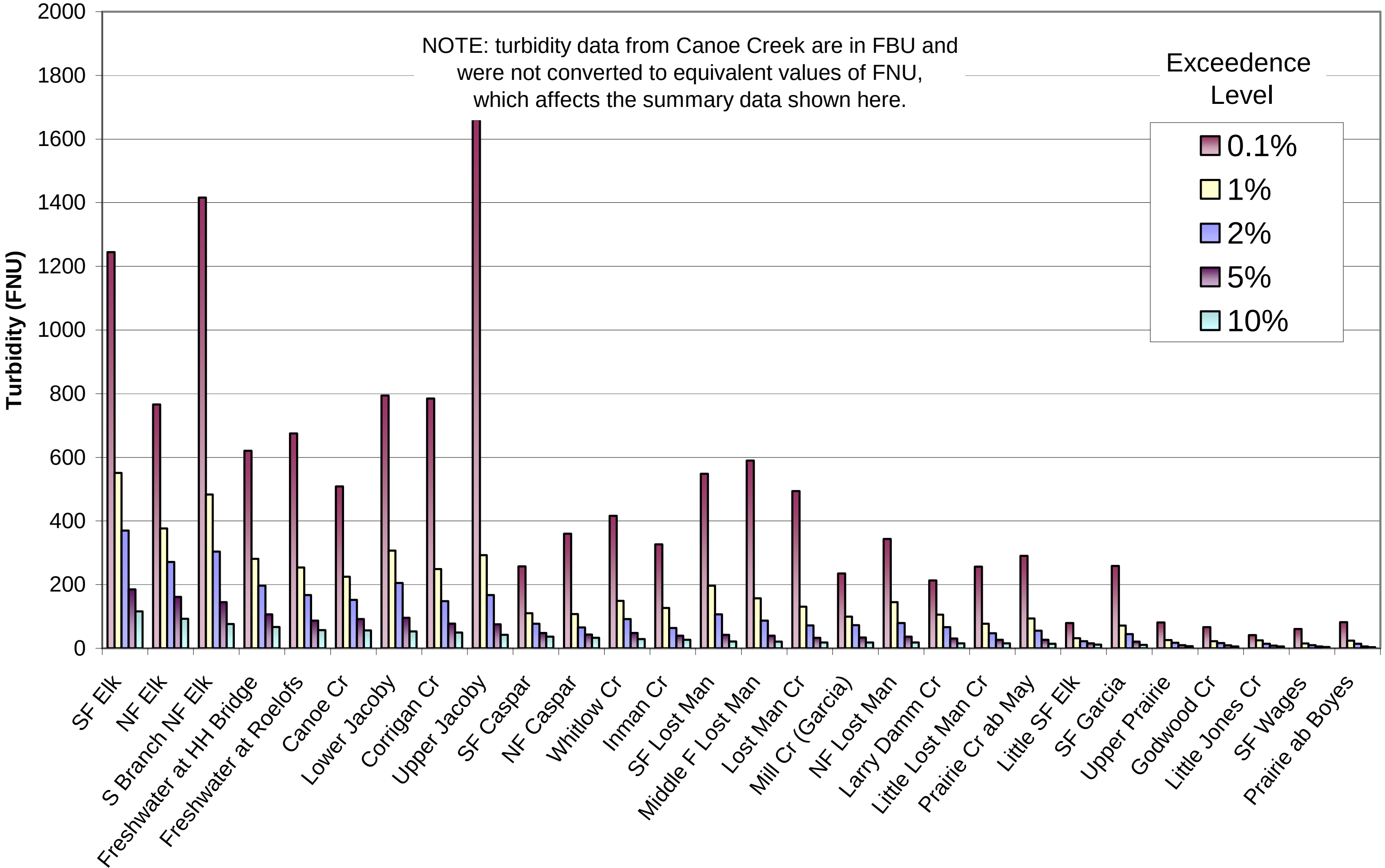


Figure 6. Turbidity exceedences for WY2005.

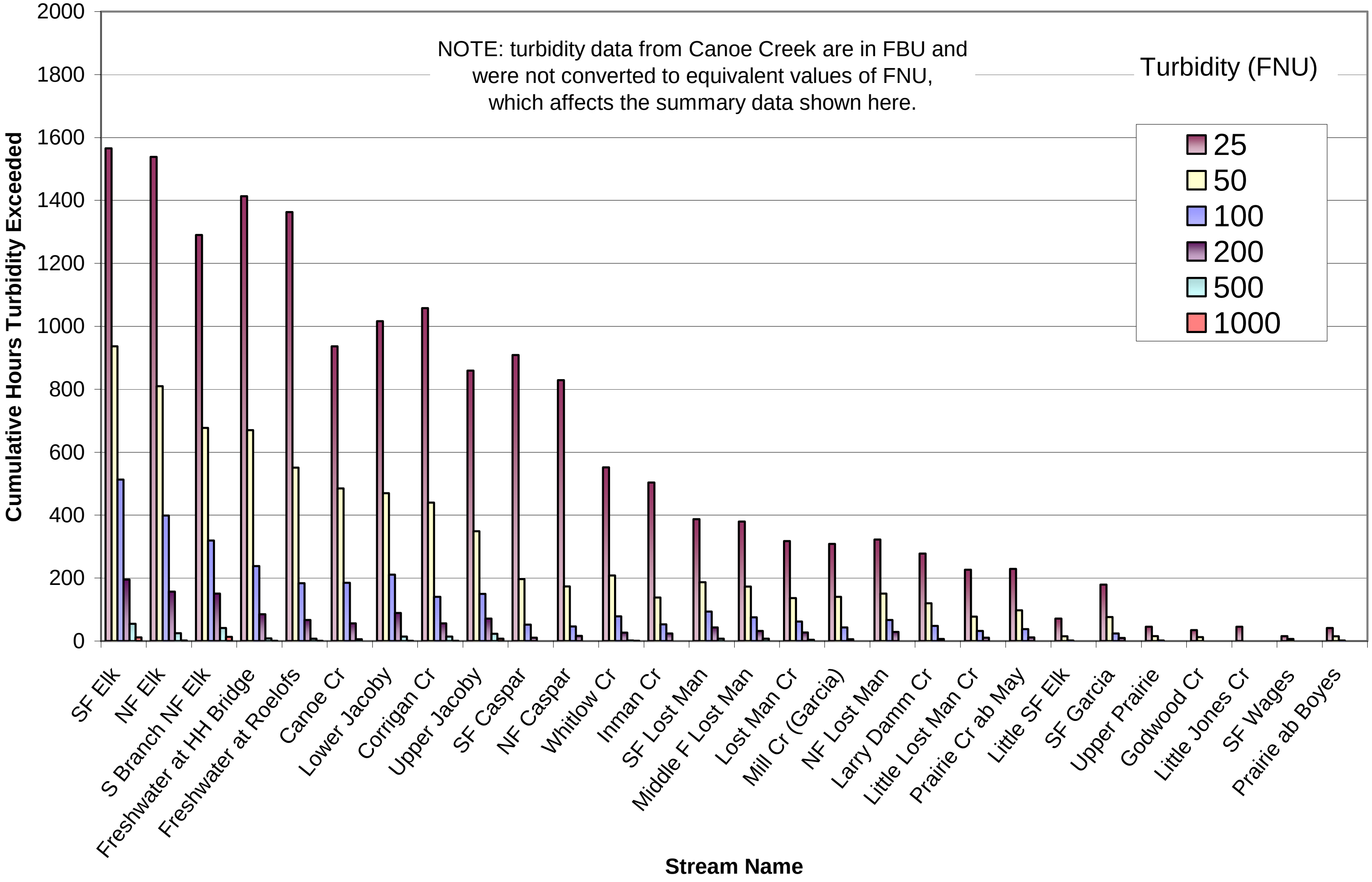


Figure 7. Turbidity durations for WY2005.

Rainfall Depths and Frequencies

Table 7 lists rainfall depths and recurrence intervals (RI) for WY2003-2005 for annual and multi-day depths for rainfall stations near clusters of turbidity stations used in this analysis. These station data show that rainfall varied across years and locations across the north coast, with shorter-term depths (single and multi-day) generally exhibiting greater variability.

Table 7. Rainfall depths and respective recurrence intervals (RI) at various durations for rainfall stations representing sub-areas within the study area. (note: "POR" means station period of record in years).

Representative Gage(s)	**Little Jones Creek**	**Prairie Creek Tribs**	**Humboldt Bay Tribs**	**Mendocino County Streams**
Station Name	Gasquet RS	Prairie Cr SP	Eureka WSO	SF Caspar
POR (yrs)	56	67	119	34
Lat	41.833	41.300	40.800	39.347
Long	-123.967	-124.070	-124.167	-123.753
ID No.	F00 3357 00	F50 6498 00	F60 2910 00	F80 1561 20
Elev (ft)	384	34	43	100
Ave Ann Ppt	90.81	66.35	39.10	44.39
Water Year	**Annual Recorded Rainfall Depth (inches)**			
WY2003	93.75	74.08	54.18	59.37
WY2004	85.34	60.05	38.75	41.92
WY2005	80.00	72.93	43.45	50.98
Water Year	**Annual Recorded Rainfall Recurrence Interval (yr)**			
WY2003	1.30	2.06	16.45	11.67
WY2004	0.67	0.47	0.97	0.70
WY2005	0.44	1.82	2.30	3.01
Water Year	**Maximum Daily Recorded Rainfall Depth (inches)**			
WY2003	3.84	4.2	6.79	3.92
WY2004	6.38	4.25	1.89	2.39
WY2005	5.26	2.46	1.77	1.89
Water Year	**Maximum Daily Recorded Rainfall Recurrence Interval (yr)**			
WY2003	0.59	3.20	1475	6.22
WY2004	3.81	3.38	0.68	0.82
WY2005	1.67	0.49	0.56	0.42
Water Year	**Maximum 2-Day Recorded Rainfall Depth (inches)**			
WY2003	5.96	7.20	8.82	5.54
WY2004	9.24	3.20	2.69	3.58
WY2005	8.70	4.37	3.05	3.37
Water Year	**Maximum 2-Day Recorded Rainfall Recurrence Interval (yr)**			
WY2003	0.78	6.47	469	5.13
WY2004	3.39	0.45	0.85	1.02
WY2005	2.66	0.98	1.23	0.86
Water Year	**Maximum 3-Day Recorded Rainfall Depth (inches)**			
WY2003	9.04	8.4	9.04	6.92
WY2004	10.29	3.83	3.14	3.92
WY2005	11.93	4.8	3.43	4.77
Water Year	**Maximum 3-Day Recorded Rainfall Recurrence Interval (yr)**			
WY2003	1.48	5.28	157	6.75
WY2004	2.44	0.37	0.71	0.73
WY2005	4.69	0.65	0.93	1.38

The data presented in Table 7 are only estimates of rainfall within the study watersheds due to differences in location, elevation, and other factors between the rainfall station used and the watershed it is intended to represent. As mentioned earlier, only the South Fork Caspar Creek (**SFC**) and the Prairie Creek gages have rain gages located within their watersheds.

WY2003 was the wettest among the three years analyzed, with annual rainfall ranging from 1.3 to 16.4 year recurrence intervals (RI). Records were set in late December, 2002, for daily and multi-day rainfall depths at the Eureka WSO rainfall gage. In WY2003 and WY2005, recurrence intervals for annual rainfall indicated heavier rainfall toward the south of the study area (RI = 11.7 years for WY2003 and 3.01 years for WY2005 at SF Caspar) with lower rainfall to the north (RI = 1.3 years for WY2003 and 0.44 years for WY2005 at Gasquet RS). In WY2004, rainfall was relatively low across the region.

Watershed Characteristics Explaining Turbidity

Watershed analytical results are tabulated in Appendix C. Multiple regression analyses results are shown in Table 8. For both series (all streams and just Humboldt County streams), the best fit included just two explanatory variables: clearcut equivalent area for the period 10-15 years before WY2005 turbidity data (CCE 10-15) and drainage area (DRA). Other models using just harvest rate (including CCE 0-15, a longer-term average annual harvest rate) also performed well. The Humboldt County stream subset had a superior fit over that for all streams, as indicated by substantially higher adjusted R-squared values.

Table 8. Multiple regression analysis results for all streams and the subset including just Humboldt County streams (bold font indicates best fit in each series).

Explanatory Variables Used with WY2005 Turbidity at 10% Exceedence (10%TU)	***AIC***	***Residual Standard Error (RMSE)*** [1]	***Adjusted R-squared***	***F-statistic***	***p-value***
All Streams except Canoe Creek (N = 27)					
Fit 1 (CCE 0-15)	244.6	20.90	0.48	24.80	3.96E-05
Fit 2 (CCE 0-15, DRA)	242.4	19.70	0.53	15.90	3.96E-05
Fit 3 (CCE 10-15)	245.9	21.40	0.45	22.50	7.26E-05
Fit 4 (CCE 10-15, DRA)	**236.1**	**17.50**	**0.63**	**23.30**	**2.35E-06**
Humboldt County Streams except Canoe Creek (N = 19)					
Fit 1 (CCE 0-15)	171.3	19.80	0.63	31.30	3.19E-05
Fit 2 (CCE 0-15, DRA)	172.6	20.10	0.62	15.60	1.77E-04
Fit 3 (CCE 10-15)	163.0	15.90	0.76	57.70	7.37E-07
Fit 4 (CCE 10-15, DRA)	**158.1**	**13.70**	**0.82**	**42.50**	**3.96E-07**

[1] RMSE values are in FNU turbidity units

Three groups of turbidity sites are listed in Table 9: 1) those with zero harvest for the period 1990-2004 (including several predominantly old-growth watersheds), 2) those watersheds with relatively low harvest rates (< 1.5%/year CCE 0-15), and 3) those with higher harvest rates (>1.5%/year CCE 0-15). As mentioned earlier, Canoe Creek was excluded because a large proportion of the watershed was burned by wildfire in 2005. The finding that harvest rate was the dominant watershed variable explaining high turbidity exceedence values is consistent with the results of Klein (2003). Interestingly, shorter–term harvest windows (CCE 0-5 and CCE 0-10, representing annual average harvest rates for 10 and 5years preceding WY2005, respectively) performed less well in the regressions. Possible interpretations might be that logging practices 10 to 15 years ago were more damaging than recent logging, or that there was a delayed effect triggered by wet conditions in WY2005, or just an artifact of the data set used.

Table 9. Harvest rates, WY2005 10% turbidity exceedences, and degrees to which turbidity durations of harvested watersheds exceeded those with zero and lower harvest rates.

Watershed	***Site Code***	***Drainage Area (DRA, sq mi)***	***Annual Clearcut Equivalent Area, 1990-2004 (CCE 0-15; %)***	***2005 10% Turbidity (10%TU, FNU)***	***% above zero harvest group average***	***% above lower harvest group average***
Prairie Cr above Boyes Cr	PAB	7.68	0.00%	3	---	---
Little Jones Creek	LJC	8.60	0.00%	5	---	---
Godwood Creek	GOD	1.48	0.00%	6	---	---
Upper Prairie Creek	PRU	4.16	0.00%	6	---	---
Little South Fork Elk River	ESL	1.18	0.00%	12	---	---
Little Lost Man Creek	LLM	3.52	0.00%	16	---	---
Larry Damm Creek	LDC	1.84	0.00%	16	---	---
South Fork Lost Man Creek	SFL	3.94	0.00%	22	---	---
Lost Man Creek at Hatchery	LMC	12.08	0.00%	18	---	---
North Fork Lost Man Creek	NFL	2.22	0.00%	18	---	---
Prairie Cr above May Cr	PRW	12.88	0.00%	14	---	---
Middle Fork Lost Man Creek	MFL	2.26	0.01%	21	---	---
Zero Harvest Group Averages =		***5.15***	***0.00%***	***13***	***---***	***---***
South Fork Caspar Creek	SFC	1.58	0.05%	37	182%	---
Mill Creek (Garcia R Trib)	MIL	3.63	0.68%	18	38%	---
North Fork Caspar Creek	NFC	1.87	0.74%	33	153%	---
SF Wages ab Center Gulch	SFW	1.11	0.85%	4	-69%	---
South Fork Garcia R	SFK	1.33	1.02%	11	-17%	---
Lower Harvest Group Averages =		***1.90***	***0.67%***	***20***	***58%***	***---***
Upper Jacoby Creek	UJC	5.83	1.57%	42	224%	111%
Lower Jacoby Creek	JBW	13.56	1.58%	53	308%	165%
South Fork Elk at M. Bohannon's	SFM	19.30	1.61%	116	792%	480%
S Branch NF Elk River	ENS	1.89	1.63%	76	483%	279%
Inman Creek (Garcia R Trib)	INM	7.53	1.71%	26	102%	31%
Corrigan Creek	ESC	1.58	2.40%	50	284%	150%
Freshwater Creek at Roelofs	FTR	12.77	2.74%	57	338%	185%
Whitlow Creek (Garcia R Trib)	WHI	1.90	2.99%	29	124%	45%
Freshwater Cr at HH Bridge	HHB	28.12	3.61%	67	415%	235%
North Fork Elk River	KRW	22.17	3.65%	93	615%	365%
Higher Harvest Group Averages =		***11.47***	***2.35%***	***61***	***369%***	***205%***

Table 10 is a correlation matrix including the 10%TU and all forms of harvest rate (CCE) variables. Although the longest-term (15-year) annual average harvest rate (CCE 0-15) was slightly inferior to the rate for an earlier period (CCE 10-15, spanning 1990-1994) in the regression analysis, it was the strongest correlate with 10%TU. Consequently, CCE 0-15 was used to estimate turbidity-discharge rating curves for modeling biological cumulative watershed effects (CWE) in Part B of this report.

Table 10. Correlation matrix of harvest rate variables and 10%TU.

	10% TU	***CCE 0-15***	***CCE 0-10***	***CCE 0-5***	***CCE 10-15***	***CCE 5-10***
10% TU	1.00					
CCE 0-15	0.71	1.00				
CCE 0-10	0.60	0.94	1.00			
CCE 0-5	0.60	0.78	0.87	1.00		
CCE 10-15	0.69	0.81	0.57	0.40	1.00	
CCE 5-10	0.44	0.86	0.87	0.51	0.59	1.00

Turbidity Rating Data and the Lower Bound Line

Figures 8 through 18 are scatterplots of discharge versus turbidity using WY2005 data for eleven (11) Humboldt County continuous turbidity sites with more than 3 mi^2 in contributing drainage area. Rating curves shown were derived by simple least squares regression (LSR) that specifies a y-intercept of zero to facilitate comparisons.

Several factors related to erosion and sedimentation processes contribute to the scatter of rating points. Most important are hysteresis, lack of synchronicity between the storm turbidigraph and hydrograph peaks, and sediment depletion (Walling and Webb, 1988). The plot for Upper Prairie Creek (PRU) in Fig. 9 provides a good example of hysteresis loops, demonstrating the often large differences in turbidity for a given discharge on the rising limb versus the falling limb of a storm hydrograph.

We have highlighted the ‘Lower Bound Line’ in Figures 8-18 as a line delineating the relatively sharply-defined lower edge of the scatter of points. As shown, two or more segments can be delineated to form the lower bound of the data, and slopes of the higher segments (those at higher levels of discharge and turbidity) are typically steeper than lower segments, indicating greater increases in turbidity with increasing discharge. This is especially true of the more intensively harvested watersheds for which turbidity rises dramatically above discharges of 20 to 30 cfs/sq. mi., as exemplified in Figures 12-17. Higher lower bound line segments were more difficult to delineate due to fewer points and greater diffusivity. Because of the greater confidence associated with delineating the lowest segment, this was used in subsequent analyses as a diagnostic for watershed condition relative to turbidity-producing erosion and sedimentation processes.

Hydrologically, data points located along the bottom edges of the scatterplots represent stormflow recession conditions when turbidity is relatively low for a given discharge.

Because recessional stormflows compose a much larger part of the winter runoff season than rising limbs or peaks, biological ‘dose’ is highly dependent upon recessional conditions. Therefore, recessional limb turbidity and the lower bound line, described by these data, serve as convenient tools for assessing chronic turbidity. Obviously, if lower bound lines were used to estimate suspended sediment loads, the result would be a gross under-estimation. As discussed in the Part B of this report, use of lower bound lines results in a very conservative characterization of conditions for fish, one that under-represents the actual exposure of stream biota to turbidity.

Also notable in Figures 8-18 is the spread of points above the lower bound line. Scaling of the vertical axes in some plots was adjusted to show the scatter of data, with the sites having more intensive land use (higher harvest rates) requiring scales spanning 0 to 1000 FNU to accommodate the data, while pristine watersheds and those without recent (within the previous 15 years) required vertical scales only spanning 0 to 100 and 0 to 500 FNU, respectively. As with the lower bound line, an upper bound line could be constructed to envelope the scatter, thus capturing peak flow and turbidity conditions as well. However, the upper margin of the plots is more diffuse, so delineating upper bound lines would be more subjective. Further exploration of additional approaches to using turbidity rating curves as a tool for characterizing and contrasting watershed conditions seems warranted.

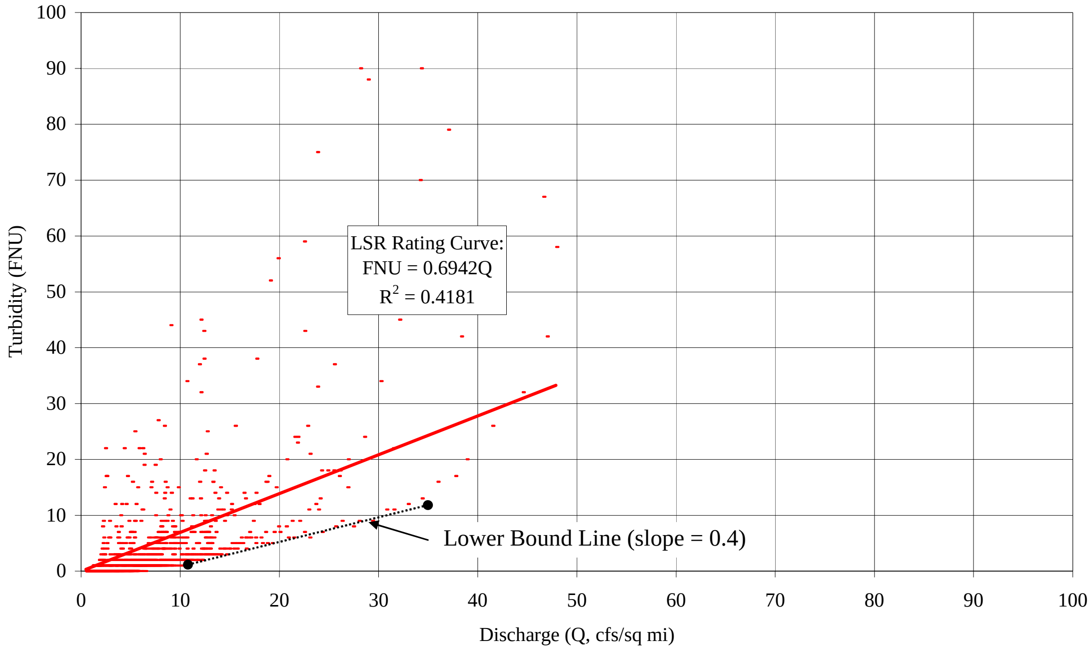


Figure 8. Turbidity lower bound line for Prairie Creek above Boyes (PAB), WY2005.

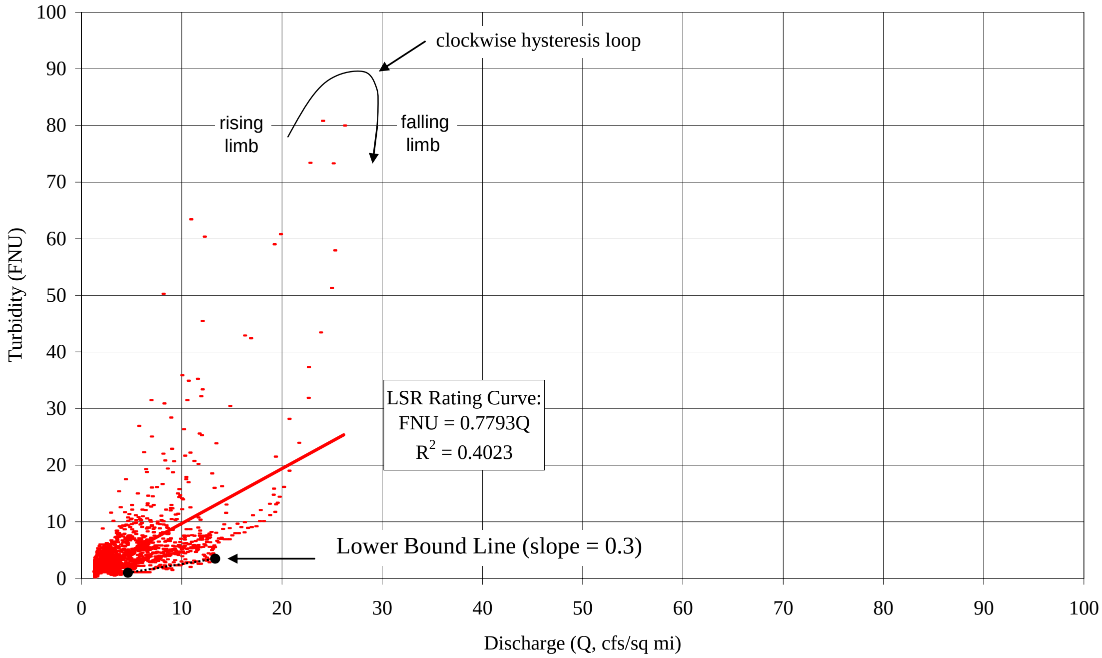


Figure 9. Turbidity lower bound line for Upper Prairie Creek (PRU), WY2005.

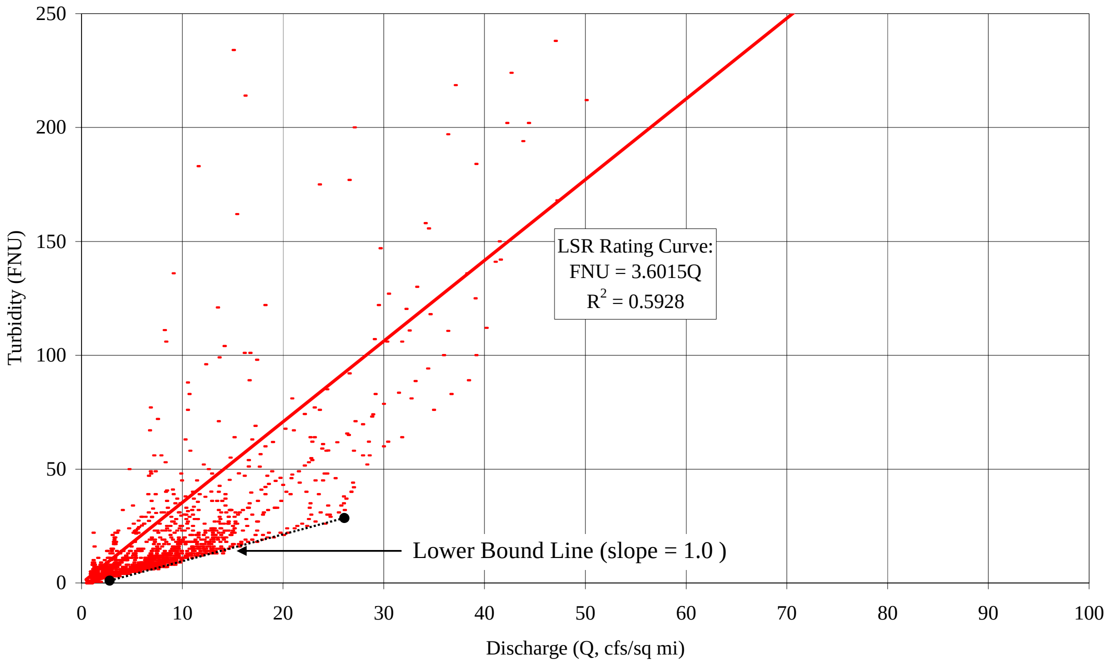


Figure 10. Turbidity lower bound line for Lost Man Creek (LMC), WY2005.

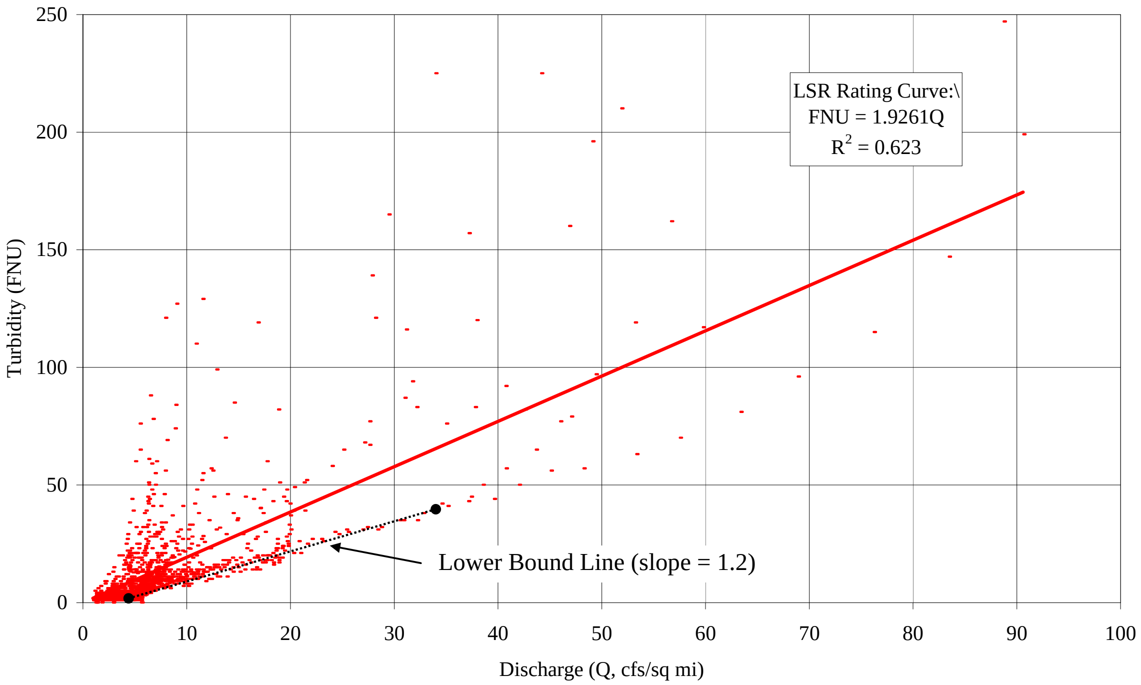


Figure 11. Turbidity lower bound line for Prairie Creek above May (PRW), WY2005.

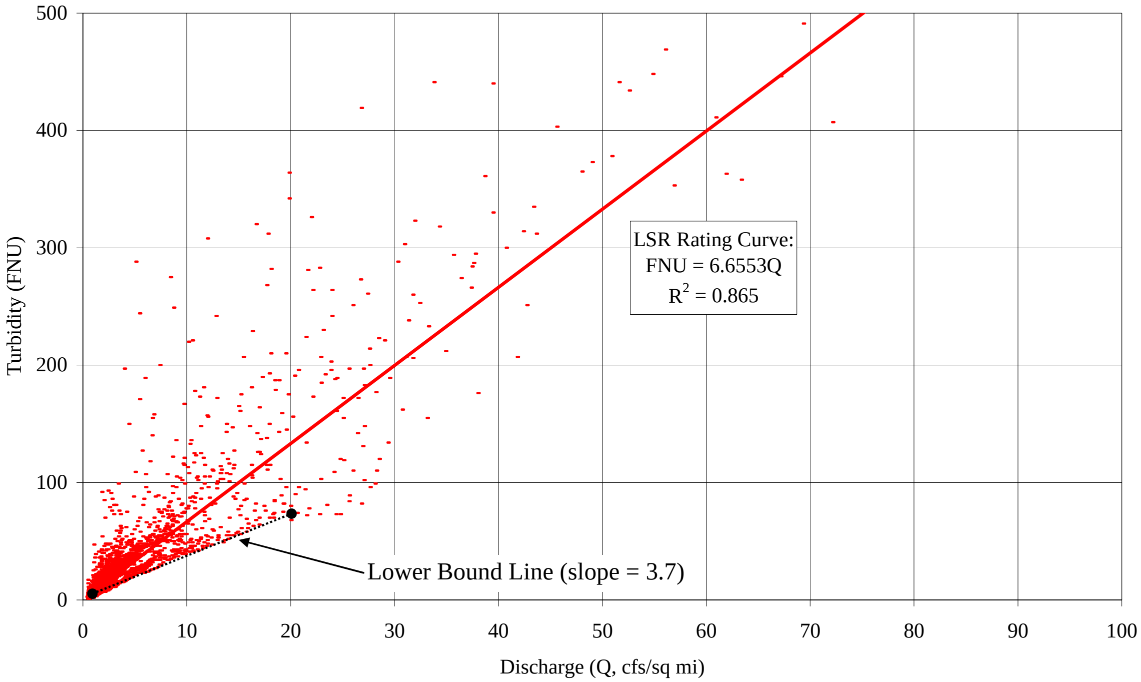


Figure 12. Turbidity lower bound line for Lower Jacoby Creek (JBW), WY2005.

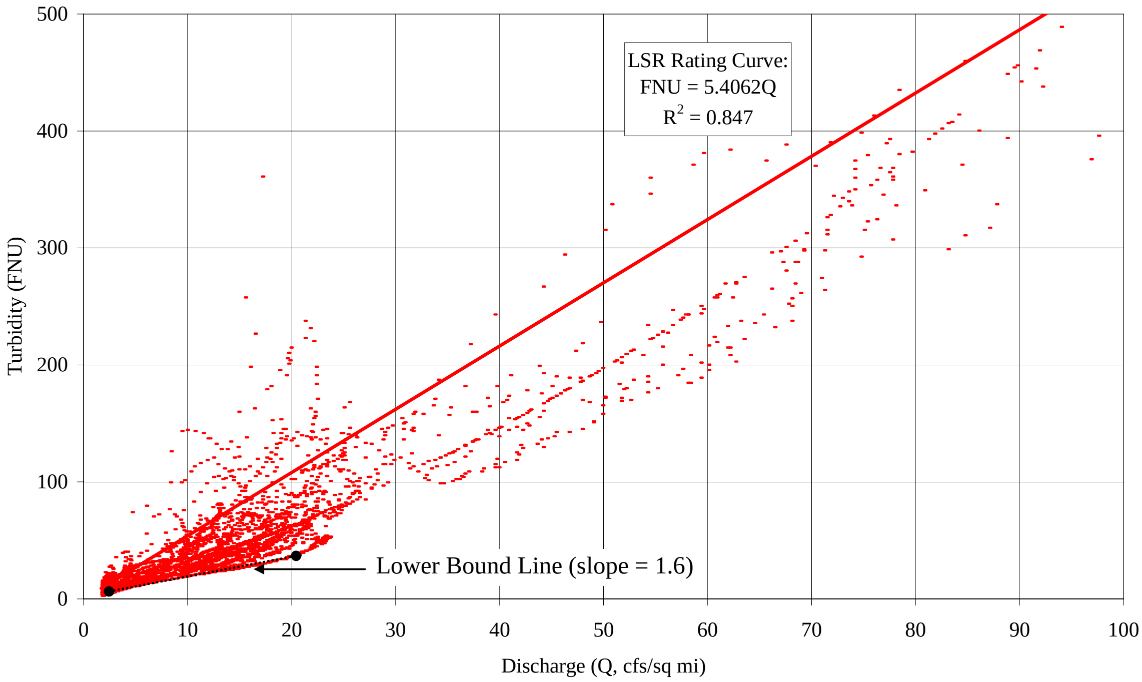


Figure 13. Turbidity lower bound line for Upper Jacoby Creek (UJC), WY2005.

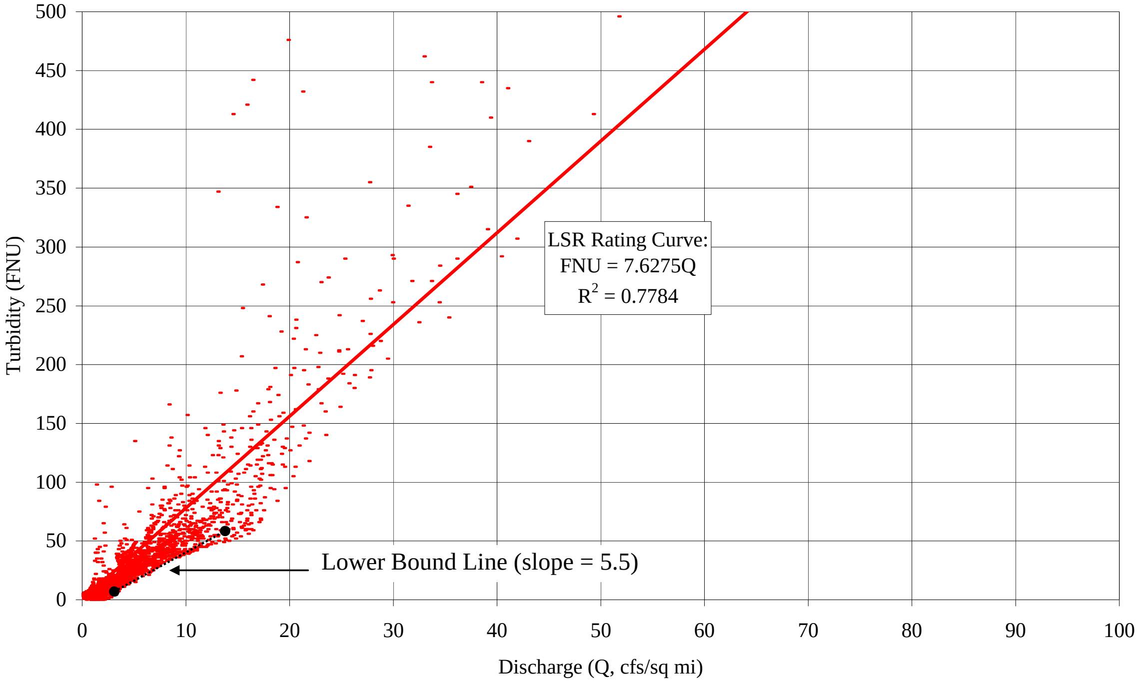


Figure 14. Turbidity lower bound line for Freshwater Creek at Roelof’s (FTR), WY2005.

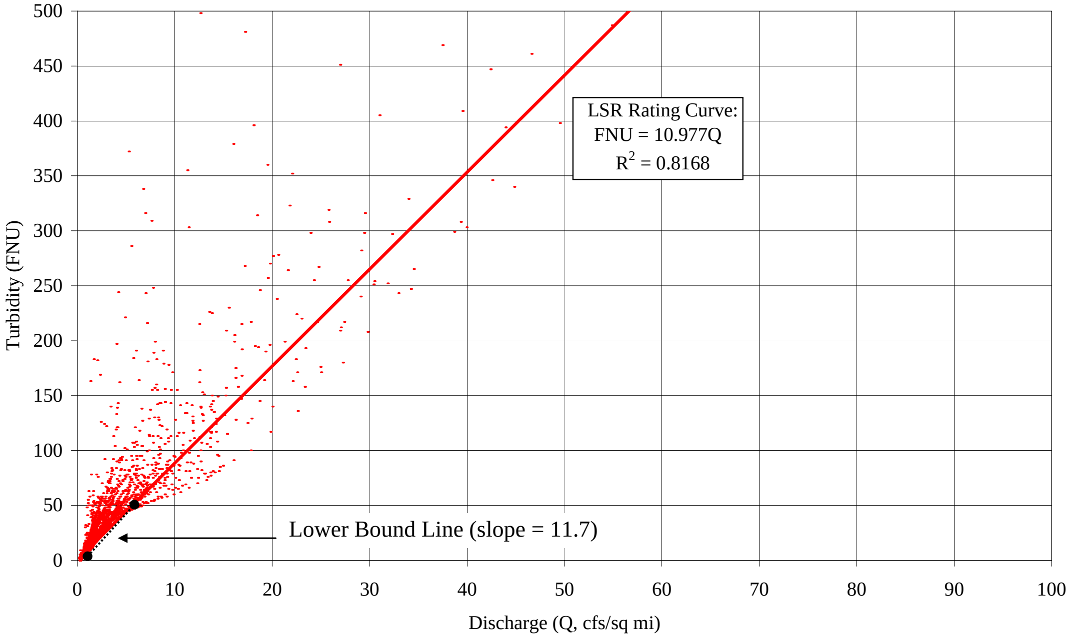


Figure 15. Turbidity lower bound line for Freshwater Creek at Howard Heights Bridge (HHB), WY2005.

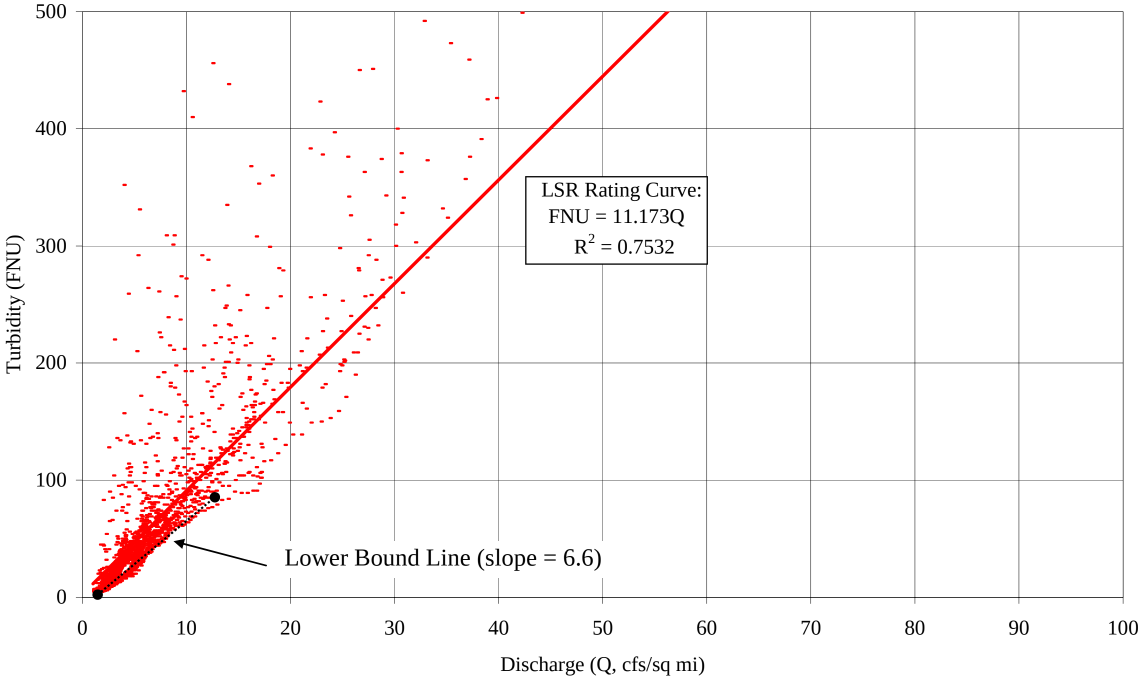


Figure 16. Turbidity lower bound line for NF Elk River at Wrigley's (KRW), WY2005.

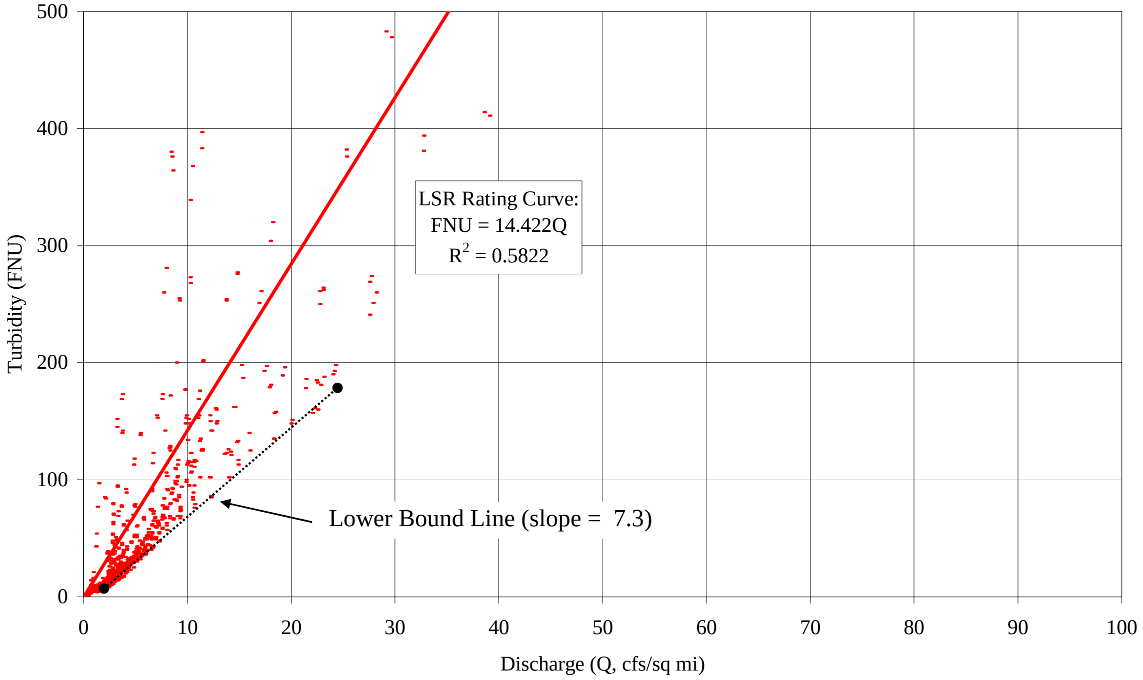


Figure 17. Turbidity lower bound line for SF Elk River at Bohannon's (SFM), WY2005.

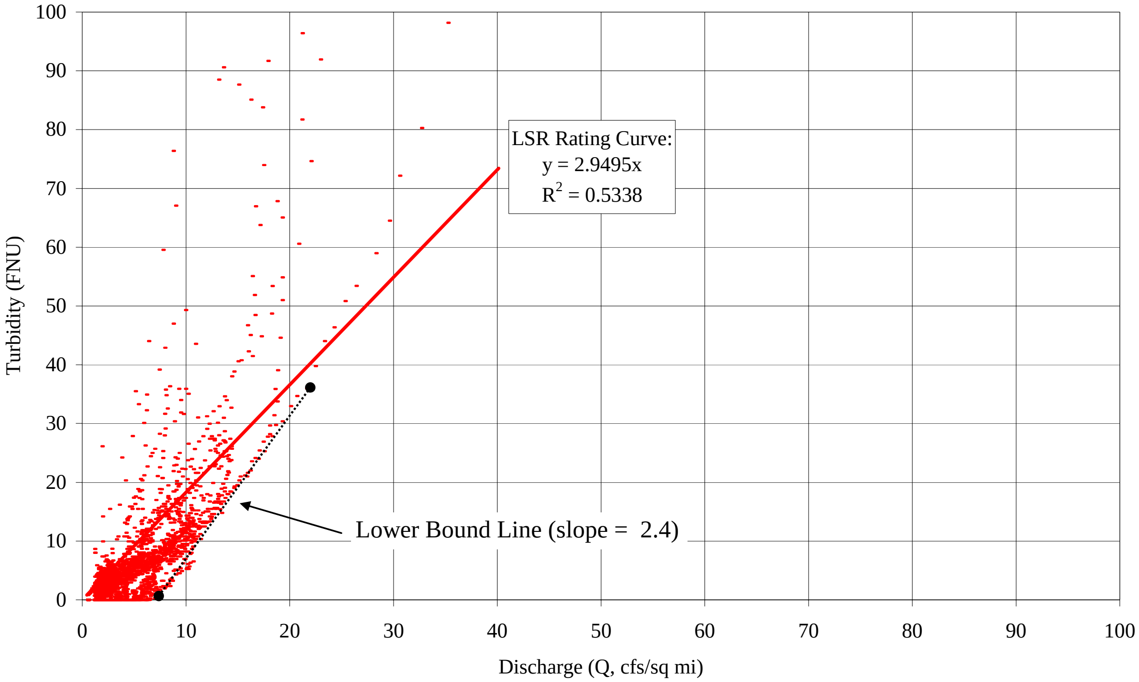


Figure 18. Turbidity lower bound line for Little Lost Man Creek (LLM), WY2005.

Figure 19 and 20 show the same ten streams plotted with the least squares regression (LSR) rating curves (characterizing central tendency) and lower bound lines, respectively.

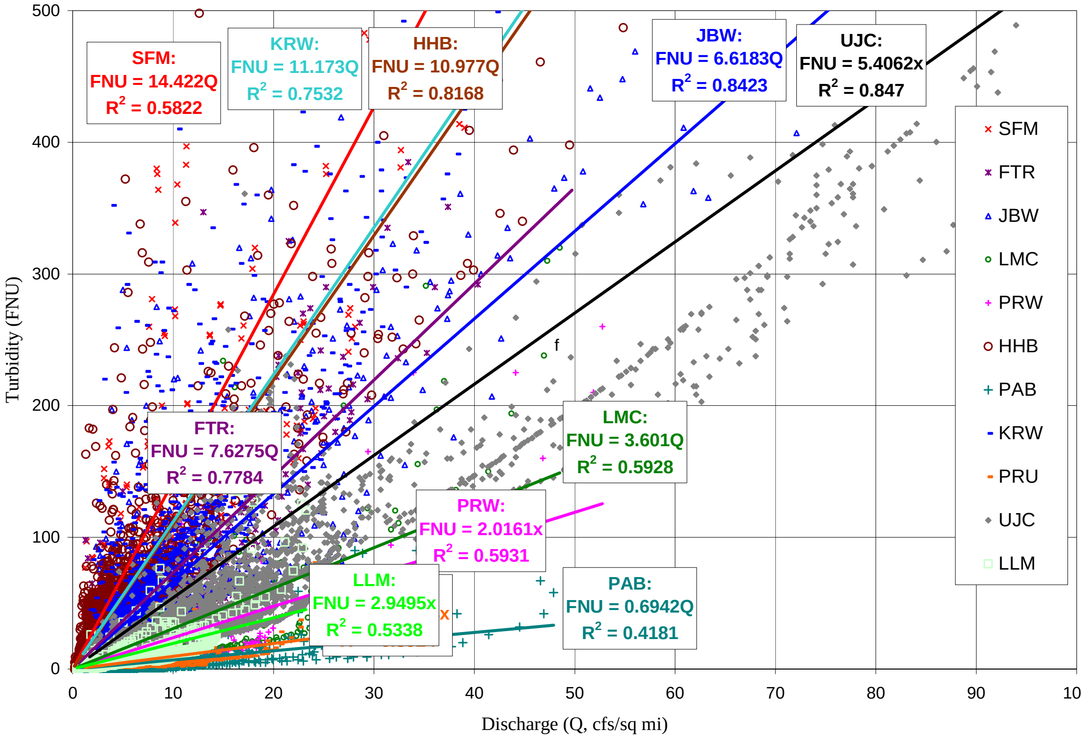


Figure 19. Least squares regression turbidity rating curves for north coast streams, WY2005.

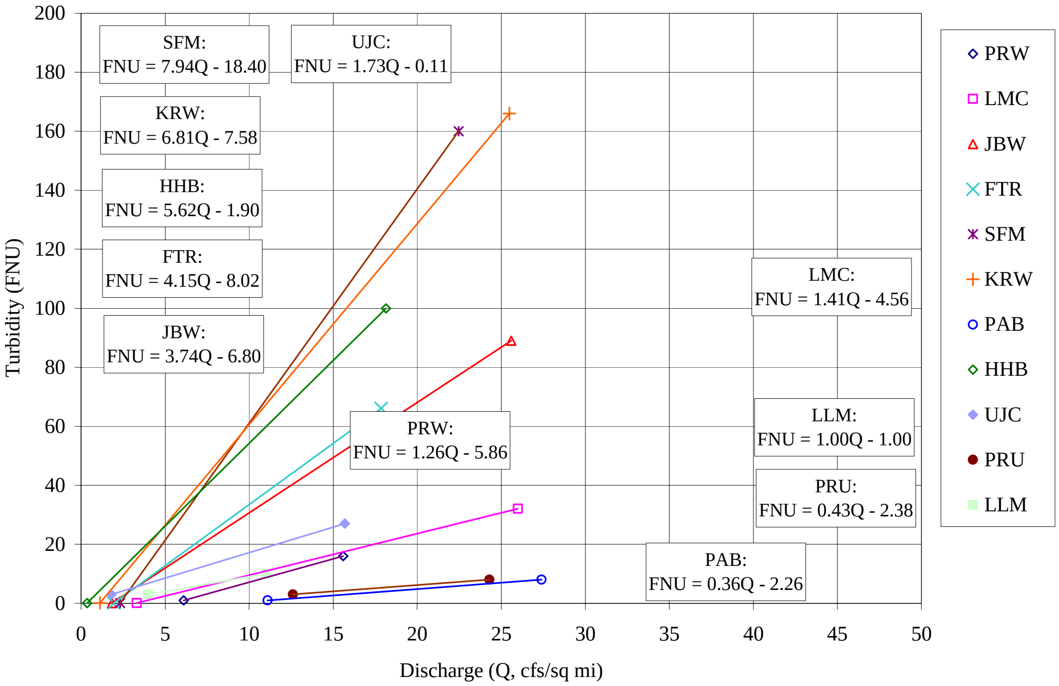


Figure 20. Lower bound lines for north coast streams, WY2005.

To evaluate the effects of land use, specifically timber harvest, on turbidity as a function of discharge, Figures 21 and 22 plot harvest rate (expressed as clearcut equivalent area averaged for the preceding 15 years, or CCE 0-15) against the least squares regression line slopes (LSS) and lower bound line slopes (LBS), respectively. In both cases, a direct relationship is exhibited between land use and the slope of the turbidity-discharge relationship for the group of ten streams. Also in both cases, the strength of the relationship was much improved when South Fork Elk River (**SFM**) was omitted. The reason for SFM to deviate from the group is not known, but explanations likely relate to geology, ‘legacy’ erosion features, and land use drivers not quantified in this study. However, for the ten other streams, a strong relationship exists between harvest rate and turbidity rating curve slope, as indicated by the improved R^2 when **SFM** is omitted.

To estimate relationships between turbidity and discharge (i.e., turbidity rating curves) as a function of harvest rate (CCE 0-15), the stronger equation resulting from the data plotted in Figure 22 (for the ten streams, excluding SFM) was used:

$$\text{Lower Bound Line Slope} = 1.4063(\text{CCE } 0\text{-}15) + 0.904$$

Turbidity rating curves were computed for average annual harvest rates ranging from 0 to 6% using this equation (Fig. 23). The biological analysis in Part B uses these rating curves, based on very conservative estimates of turbidity for a given discharge, to develop turbidigraphs for assessing biological cumulative watershed effects. For comparison, rating curves based on least squares regression (LSR) are also shown in Fig. 23, which would yield nearly twice the turbidity for a given discharge compared to using lower bound line slopes.

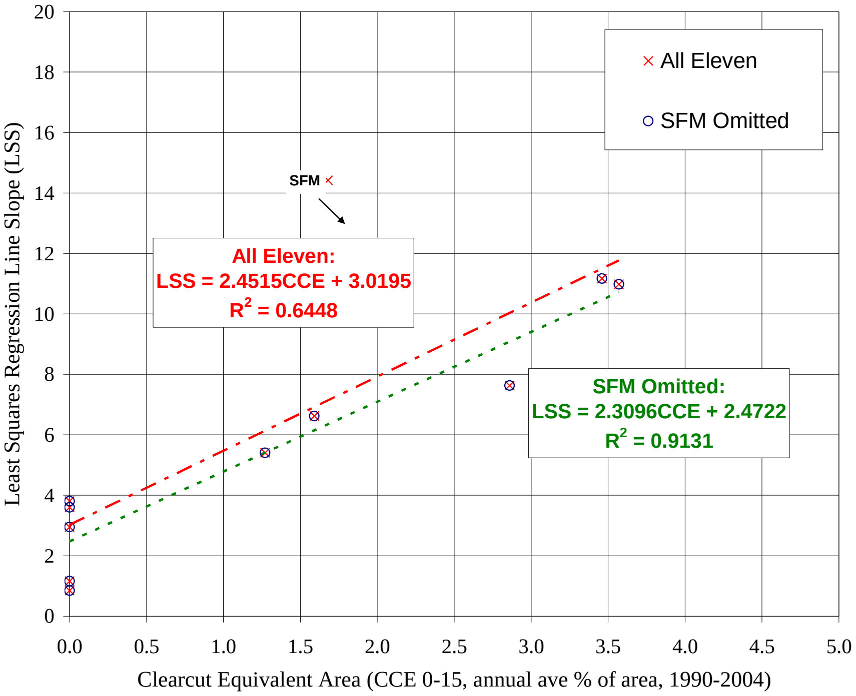


Figure 21. Clearcut equivalent area (CCE 0-15) vs least squares regression rating curve line slope (LSS) for north coast streams, WY2005.

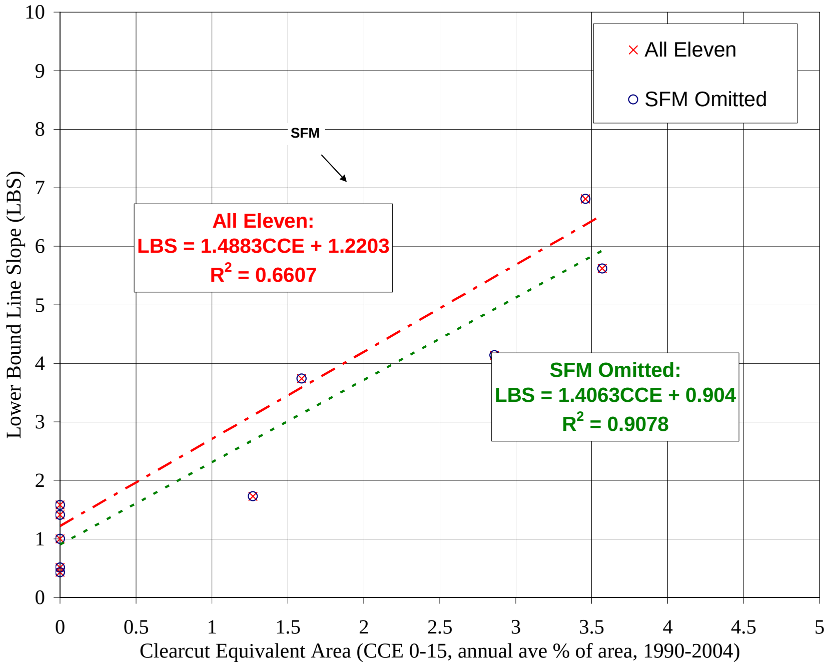


Figure 22. Clearcut equivalent area (CCE 0-15) vs lower bound line rating curve line slope (LBS) for north coast streams, WY2005.

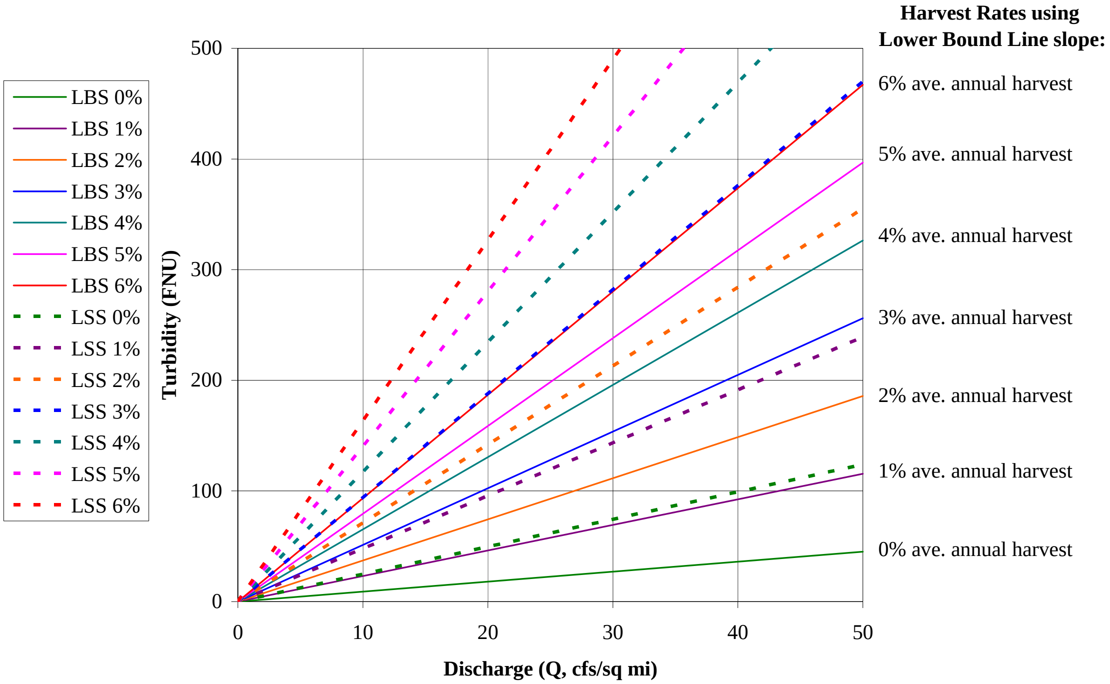


Figure 23. Turbidity rating curves from lower bound line (LBS) and least squares regression (LSS) line slopes at various levels of average annual harvest (CCE 0-15).

The South Fork Elk River (site **SFM**) was the largest outlier among the study streams: the 10% turbidity was much higher than the timber harvest rate suggested. One factor why SFM was more turbid than the other sites with similar harvest rates may be due to the underlying geology. **SFM**, along with several other Humboldt Bay tributaries, has a substantial portion of its area underlain by the highly erodable Wildcat Formation (see Appendix C). The sedimentary rock units of the Wildcat Formation readily weather into non-plastic clayey silts and clayey sands that are susceptible to colluvial processes. The colluvial soils derived from Wildcat Formation can be especially prone to shallow soil slips and debris slides if present on relatively steep slopes (Marshall and Mendes, 2005).

Figure 24 shows 10% turbidities versus percent Wildcat Formation for the Humboldt County watersheds (note that the three smallest Wildcat watersheds are located within the North and South Fork Elk watersheds; **ENS** lies within the North Fork (**KRW**), **ESC** and **ESL** lie within the South Fork (**SFM**)). Three linear fits are included: one for all the Humboldt County watersheds and two subsets include only the larger and the smaller watersheds. The ‘all’ group and the smaller watersheds have poor relationships between turbidity and Wildcat percentage, but the larger watersheds have a strong direct relationship.

The three smaller Wildcat watersheds, **ENS**, **ESC** and **ESL**, have turbidities less than the two larger watersheds, **SFM** and **KRW**, which have similar Wildcat percentages. As noted earlier, drainage area was one of two watershed characteristics that best explained turbidity

(Table 8). The other characteristic, harvest history, is clearly a factor since the nearly pristine old growth watershed **ESL** has by far the lowest turbidity despite having the highest percent area in Wildcat Formation. The next lowest turbidity for a Wildcat watershed, **ESC** (10% turbidity = 50 FNU) is over four times greater than **ESL**'s 10% turbidity (12 FNU).

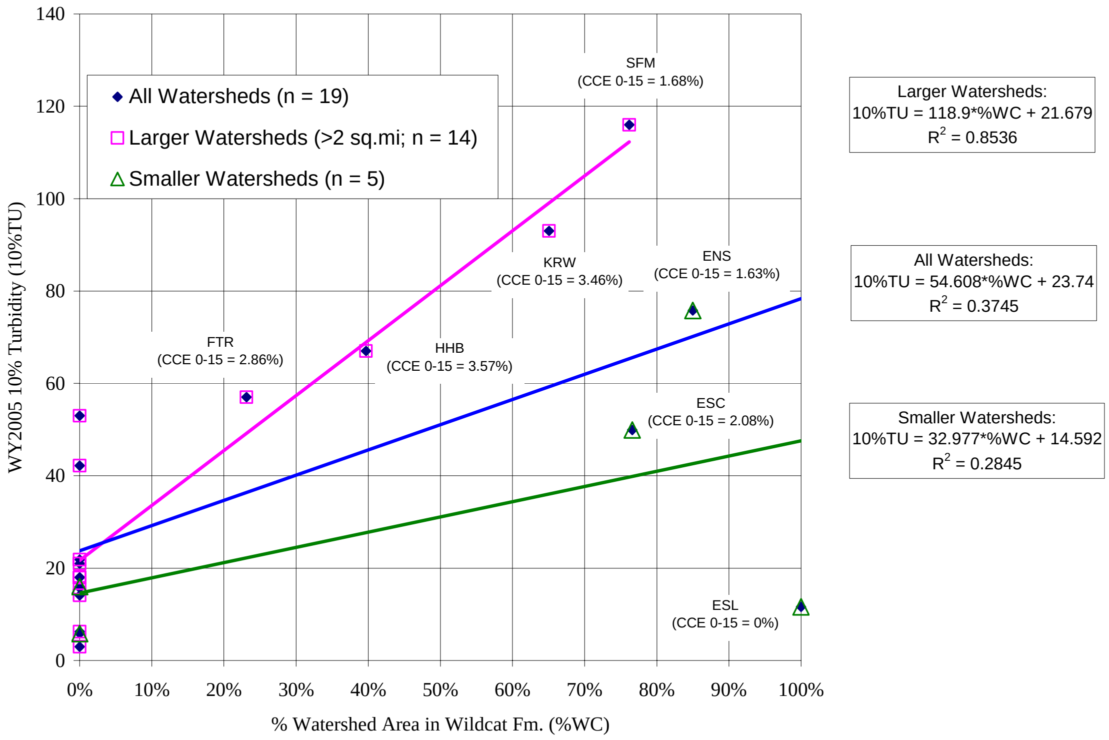


Figure 24. WY2005 10% turbidities vs percent of watershed in Wildcat Formation, Humboldt County watersheds.

Any tool used to indicate watershed condition must be independent of annual variations in hydrologic conditions. To evaluate the multi-year stability of the lower bound line slope (LBS), lower bound line x-y coordinates from fives years (WY2001-2005) from two streams (UJC and PRU) are plotted in Figure 25 (Note: this comparison is made using unconverted OBS-3 data). The data plotted in Figure 25 represent multi-year turbidity rating data extracted from lower bound line coordinates. In the Prairie Creek watershed, rainfall for WY2001-05 ranged from 38.3 inches (WY2001) to 63.0 inches (WY2003). Peak discharges in Upper Prairie Creek (**PRU**) ranged from 28 cfs (WY2001) to 242 cfs (WY2004), a nearly ten-fold difference.

The linear grouping of points and the high R^2 values indicate that the slope of the lower bound line was temporally consistent despite large annual differences in rainfall and runoff. Further, the slopes are different for both streams. Upper Jacoby Creek (**UJC**) exhibits a much steeper slope. Having been harvested at a rate of about 1.3% per year for the period of WY1990-2005 (CCE 0-15), this equates to about 20% of the total area harvested in that period. Upper Prairie Creek (**PRU**) is dominantly old-growth redwood forest, and has a slope one-quarter that of Upper Jacoby.

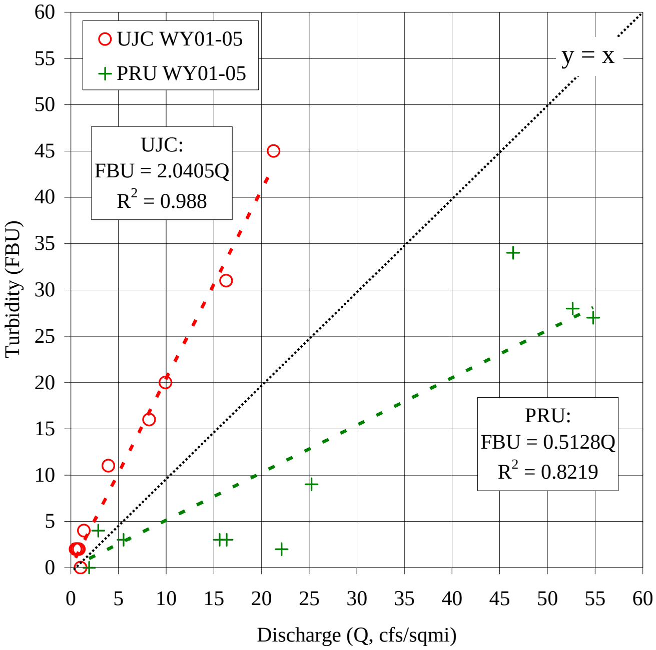


Figure 25. Upper Jacoby Creek (UJC) and Upper Prairie Creek (PRU) turbidity lower bound line coordinates and regression lines, WY2001-2005 (OBS-3 data).

Discussion

Basin geomorphic characteristics reflect basin-shaping processes and susceptibility to erosion-accelerating disturbances. These seven factors were derived for the study watersheds to serve as surrogates for erosional susceptibility because there is no direct measure of this characteristic:

- average watershed slope (AWS),
- basin relief (RLF),
- hypsometric integral (HYP),
- intermittent stream density (ISD)
- perennial stream density (PSD),
- total stream density (TSD), and
- SINMAP area (%) with factor of safety less than one (SIN<1).

However, their contribution in explaining turbidity variations was insufficient in the best fit regression models after the addition of harvest rate and drainage area. Certainly, natural factors that determine the inherent erosional susceptibility of hillslopes exert strong control on stream sedimentation and water quality, but with the exception of drainage area, those listed above had little statistical value in the regression analyses.

Undoubtedly, there are other factors at play in the range of turbidities among our study sites. One noticeable trend is that watersheds in Mendocino County had lower turbidities even though there is ongoing harvest in those watersheds. One reason for this trend may be due to winter operations, which are less prevalent in Mendocino County than in Humboldt County. Conducting timber operations during the winter period greatly increases the potential for sediment delivery because of the erosional effects of rainfall and streamflow energy on freshly disturbed ground and unsurfaced roads. Furthermore, it is clear that highly erodable geologies (e.g. Wildcat Formation) play a role in turbidity (Figure 24). Although it was not feasible to examine winter operations in this analysis, we believe harvesting during sensitive times (winter operations) in erosionally-susceptible watersheds deserves greater scrutiny.

Forest roads are widely-recognized culprits in elevated erosion and sediment delivery in the North Coast. Reid (1998) modeled effects of fine sediment production from roads using cumulative stream turbidity duration curves. Her results suggested that road-related erosion would cause large increases in chronic turbidity, elevating the duration of turbidities above 100 NTU by a factor of 73.

As mentioned above, road variables used here had little added statistical value beyond harvest rate in explaining turbidity variations, possibly resulting from incomplete and/or inaccurate road data. For example, the GIS data contained more road miles than actually exist in several watersheds where we have direct knowledge (e.g., Prairie Creek). But for most areas, road lengths are probably under-represented in ‘off-the-shelf’ data sets. Perhaps more accurate road data would have elevated the importance of road variables in explaining turbidity. But roads were indirectly accounted for in that they are closely linked to harvest rate: the density of the road network and the intensity of use rise with increasing harvest.

Our analyses demonstrate that turbidity durations vary widely among north coast streams, with several exhibiting extreme turbidity. The rate of timber harvest was the strongest watershed variable explaining differences in chronic turbidity (expressed as the 10% exceedence turbidity) among the study watersheds, with drainage are playing a subordinate role, findings that are consistent with the earlier results of Klein (2003). Comparison of WY2005 10% turbidity exceedences among zero harvest, lower harvest, and higher harvest watersheds (Table 9) showed that chronic turbidity in the more intensively harvested areas (>1.5% average annual rate) can greatly exceed that in areas with lighter harvest. In fact, were 10% turbidity used as a parameter for evaluating compliance with water quality standards (“not be increased more than 20% above naturally occurring background”), all but two study watersheds harvested within the 15 years prior to WY2005 would have been out of compliance. Most of the zero harvest watersheds (federal and state lands) used for comparison are far from pristine; old logging ‘legacy’ features, highways and freeways, and road decommissioning all likely contributed, albeit modestly, to WY2005 turbidity.

The concept of determining ‘threshold’ rates of timber harvest (i.e., rates above which environmental impacts become excessive) is not new. Reeves and others (1993) found harvest rate to be inversely associated with salmonid assemblage diversity. The California Department of Forestry and Fire Protection (CDF), in preparing draft Sensitive Watershed Criteria for the Board of Forestry, suggest timber harvest exceeding 20% of a watershed within a ten year period (equating to an annual harvest rate of 2%) could result in consideration of a watershed as “sensitive” (Munn and Cafferata 1992). Tuttle (1992) cites threshold values of 27% weighted average basal area removed and 15% of the watershed area harvested with even-aged regeneration methods within the past decade, resulting in an annual harvest rate of 1.5%-2.7%, to be used as a threshold for triggering examination of impacts to beneficial uses of water. The North Coast Regional Water Quality Control Board recently ordered that harvest rates in Elk River and Freshwater creek (two Humboldt Bay tributaries included in our analysis) be limited to curtail harvest-related landslide sediment discharges and to reduce nuisance flooding conditions (North Coast Regional Water Quality Control Board, 2006).

Because only a small percentage of north coast streams have continuous turbidity stations, the data used here are cannot be assumed to represent the full spectrum of turbidity levels within the region. However, it is feasible to conduct manual sampling to define lower bound lines for many ungaged sites for refining relationships between watershed disturbances and water quality and for determining compliance with standards. Utilizing a larger number of sites would better represent the physiographic diversity within the region, thereby providing a stronger basis for establishing defensible harvest rate limits that ensure protection of beneficial uses and for customizing and adaptively managing north coast timber harvest.

Literature Cited

Burnham, K. P. and D. R. Anderson. 2002. Model Selection and Multimodel Inference: A Practical-Theoretic Approach, 2nd ed. Springer-Verlag.

Eads, R., and J. Lewis. 2002. Continuous turbidity monitoring in streams of northwestern California. In Turbidity and other Sediment Surrogates Workshop Proceedings. Apr. 30-May 2, 2002. Reno, NV.

Janda, R.J., Nolan, K.M., Harden, D.R., and S.M. Colman. 1975. Watershed conditions in the drainage basin of Redwood Creek, Humboldt County, California. USGS Open File Report 75-568. 255 p.

Lewis, J., Eads, R., and R.D. Klein. 2007. Comparisons of turbidity data collected with different instruments. Report to California Department of Forestry and Fire Protection and the North Coast Regional Water Quality Control Board. 27 p.

Marshall, G. J., and E. Mendes. 2005. Geologic and geomorphic features related to landsliding and landslide potential in the Eel River watershed. State of California, Dept. Cons., Calif. Geol. Survey, Sacramento, CA.

Munn, J. and P. Cafferata. 1992. Draft Sensitive Watershed Criteria. Calif. Dept. of Forestry and Fire Protection. Sacramento, CA.

Nolan, K.M., and R.J. Janda. 1990. Impacts of logging on stream-sediment discharge in the Redwood Creek basin, northwestern California. In Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. USGS Prof Paper 1454. pp L1-L8.

North Coast Regional Water Quality Control Board. 2006. Order No. R1-2006-0039: Watershed-wide waste discharge requirements for timber harvesting plan activities, Salmon Creek Corporation, and the Pacific Lumber Corporation in the Elk River watershed. 39 p.

R Development Core Team. 2007. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: http://www.R-project.org.

Reeves, G. H., Everest, F. and J. Sedell. 1993. Diversity of juvenile anadromous salmonid assemblages in Coastal Oregon basins with different levels of timber harvest. Trans. Am. Fish. Soc. 122(3).

Reid, L.M. 1998. Forest roads, chronic turbidity, and salmon. Amer. Geophys. Union, 1998 Fall Meeting Abstracts. San Francisco, CA.

Sakamoto, Y., Ishiguro, M., and G. Kitagawa. 1986. Akaike Information Criterion Statistics. D. Reidel Publishing Company.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Bull. Geol. Soc. Am. v. 63. pp. 1117-1142.

Tuttle, A. 1992. Board of Forestry Sensitive Watershed Rule Package Staff Paper.

Walling, D.E., and B.W. Webb. 1988. The reliability of rating curve estimates of suspended sediment yields: some further comments. In Sediment Budgets: Proceedings of a Symposium, Porto Alegre, Brazil, 11-15 Dec., 1988. IAHS Pub. No. 174. pp. 337-350.

PART B: THE TIMBER HARVEST RATE AND CWEs

Introduction

Timber harvest is one of many land management activities contributing cumulative watershed effects (CWEs) to anadromous salmonids in north coastal California. The extent of CWEs is a function of two primary timber harvest management prescriptions: 1) how to harvest an acre and 2) how many acres to harvest over a specified time period and watershed area. The California Forest Practice Rules (FPRs) have been effective in minimizing local environmental effects attributable to the first prescription, but ineffective at addressing/assessing cumulative effects due to the second. Timber harvest activities still discharge sediment, particularly when forestland harvested once or twice before is harvested again.

A Science Review Panel was created by a March 1998 Memorandum of Understanding (MOU) between the National Marine Fisheries Service (NMFS) and The Resources Agency of California to undertake a comprehensive review of the Forest Practice Rules (FPRs) with regard to their adequacy for the protection of salmonid species. The SRP Report (1999) concludes that the primary deficiency of the FPRs is lack of a watershed analysis approach capable of assessing cumulative effects attributable to timber harvesting and other non-forestry activities on a watershed scale. While criticizing the lack of effective CWE assessment proposed in Washington's Habitat Conservation Plan for Forest Practices, Frissell (2005) states:

> *"One of the most biologically severe effects of the chronic disturbance and sediment delivery caused by forest roads and logging is increased suspended sediment in streams and rivers, with increased turbidity and reduced water quality. Exhaustive biological research on this question, reviewed by Newcombe and Jensen (1996) and Newcombe and MacDonald (1991), has shown beyond doubt that increased sediment concentration or turbidity in virtually every instance has a harmful and cumulative effect on fish health, growth, and survival."*

In commenting on timber harvesting in a North Coastal California watershed, Reid (no date, p.3) concludes:

> *"…results show that turbidity rating curves for logged tributaries are significantly higher than those for undisturbed and less-disturbed tributaries on similar rock types (Figure 1). Basin Plan objectives call for turbidities of no more than 20% over background natural levels (FEIS/FEIR, p.3.4-12, NCRWQCB 1988), but the shift in the turbidity rating curve evident in partially logged tributaries indicates that background levels are being exceeded by more than 400%."*

Despite the 1999 SRP Report recommending a scientist panel be convened to examine the rate of timber harvest, no definitive action regarding CWE thresholds has been taken. At what rate of timber harvest does cumulative fine sediment ‘leakage’ from multiple THPs in a watershed begin to be ecologically and economically significant?

An answer requires a CWE analysis that forecasts consequences from cumulative fine sediment leakage into the stream network. Our biological analysis defined ‘consequences’ through quantitative thresholds: a significant CWE occurs when a threshold has been exceeded. Two of the best physical variables for quantifying and establishing CWE thresholds in coastal California are suspended sediment and turbidity. Both respond directly and rapidly to increases in watershed disturbance and both have been quantitatively associated with biological consequences. Chronic high turbidity will impact anadromous salmonids physiologically and ultimately, if too chronic and/or high, could jeopardize population integrity.

Newcombe and MacDonald (1991) and Newcombe and Jensen (1996) synthesized past scientific literature to rank potential impacts of suspended sediment on anadromous salmonids and stream ecosystems in general. The authors evaluate the combined impact of suspended sediment (SS) concentration and continuous exposure, where dose equals the concentration of suspended sediment (mg SS/l) times duration of exposure (in continuous hours), by devising a severity-of-ill effects index (SEV). Dosage effects are ranked from lethal (SEV = 14) to nil (SEV = 0). Newcombe and Jensen (1996) later refine this general dose-response model by distinguishing salmonid life history stages.

SEV has become a tool of choice for many states formulating suspended sediment and turbidity water quality standards (e.g., Walters et al. 2001). However, use of continuous exposure in computing SEV seems more appropriate for evaluating acute effects, and considerably less ideal for quantifying many chronic ones. Acute SEV values (9 and greater) can be associated directly with quantitative salmonid impacts in Newcombe and MacDonald (1991): a stated percentage of the population may die. Suspended sediment levels must be extremely high to kill immediately upon initial exposure or soon thereafter. Most CWEs related to fine sediment are not acutely lethal. Chronic sub-lethal SEV values (8 and lower) are given no quantitative outcomes. For example, how many fewer juvenile steelhead smolts are produced if they experience “moderate physiological stress” as characterized by Newcombe and MacDonald (1991) for an SEV value of 6? Also many important cumulative effects generated by low sediment concentrations need not be evaluated under continuous exposure as required by SEV. Although SEV was not the primary tool in our CWE analysis, it complements the cumulative non-acute suspended sediment assessment of anadromous salmonids and the stream ecosystem addressed in this report.

Project Goals

Our project goals were to provide timber harvest management with a practical tool for preventing/minimizing future CWEs to stream ecosystems and anadromous salmonid populations. Objectives of this report were: 1) to show how potential CWEs on anadromous salmonids can be evaluated and 2) to quantitatively link ecological and biological thresholds caused by elevated stream turbidity to average annual timber harvest rates prevalent in North Coastal California. (Note; turbidity in the traditional units, ‘NTU’, is used in the text here for consistency with the published literature on biological effects, however data analyses use units of ‘FNU’ as in Part A).

Two analytical strategies were developed for assessing CWEs in a North Coastal California watershed. Both identify an average annual rate of timber harvest likely to cause significant CWEs to the aquatic ecosystem and anadromous salmonids between WY1991 and WY2005 in third order streams (with 5 mi^2 to 15 mi^2 watersheds). The first strategy computed the exceedence of three chronic biological turbidity thresholds for a 15-yr set of modeled Lower Bound annual turbidigraphs. These thresholds targeted general stream processes and specific physiological responses of anadromous salmonids identified in the scientific literature. This first strategy, however, cannot estimate how many fewer adult salmonids might return due to progressively higher average annual timber harvest rates. The second analytical strategy does, by modeling juvenile steelhead growth and survival-to-adult-return (SAR) as influenced by the Lower Bound annual turbidigraph that in turn is a function of the average annual timber harvest rate.

ANALYTICAL STRATEGY NO. 1: EXCEEDENCE OF CWE THRESHOLDS

Our first analytical strategy addresses the question: If the timber in a third-order North Coast watershed were harvested, at what annual rate of harvest (measured as CCE 0-15, Part A) would significant CWEs be expected? Two steps were needed: 1) establish CWE thresholds that require the exceedence of a specific magnitude and occurrence of turbidity and 2) model annual turbidigraphs at different harvest rates, then apply these chronic turbidity thresholds to the turbidigraphs and identify at which harvest rate each CWE threshold would be exceeded.

To assess the proposed CWE thresholds, we used the mainstem channel of pristine Elder Creek watershed (6.5 mi^2) in the upper South Fork Eel River basin of Mendocino County as an example. Elder Creek watershed is underlain by the Yaeger terrain of the Coastal Franciscan Belt (Mast and Clow 2000), supports a mixed forest of old growth Douglas-fir, tanoak, and madrone, and sustains a steelhead population.

Methods

This strategy required several steps: 1) construct annual daily average Lower Bound Line turbidigraphs from November 15 through June 15 for WY1991 through WY2005 under different timber harvest rates for Elder Creek. The time period November 15 through June 15 was selected because it includes steelhead spawning, egg incubation, overwinter juvenile rearing, and smolt outmigration life history stages; 2) propose three biologically significant turbidity thresholds and establish significant “chronic” exceedence probabilities for each threshold; 3) compute Lower Bound turbidity duration curves as a function of the average annual timber harvest rate; and 4) compute the number of days each biological turbidity threshold was exceeded in the Lower Bound turbidigraphs from WY1991 through WY2005, generated under each average annual timber harvest rate, to determine the average annual timber harvest rates exceeding these three CWE thresholds. The steps are described below.

1) Construct Annual Lower Bound Turbidigraphs

Daily average Lower Bound Line turbidigraphs were computed between November 15 through June 15 using: 1) daily unit runoff (cfs/mi^2) from the Elder Creek USGS stream gage (USGS Sta. No.11475560) streamflow data in WY1991 through WY2005 and 2) Lower Bound Line turbidity rating curves at 0 to 6 percent annual timber harvest rates developed in this study, using the Lower Bound turbidity rating curves in Figure 23, for baseflows less than 30 cfs/mi^2 (from previous section). Each of the 15 water years analyzed was categorized as either being Wet, Normal, or Dry.

2) Propose Three Biologically-Relevant Turbidity Thresholds

Three turbidity thresholds are proposed for North Coastal California watersheds based on the scientific literature:

Background Stream Ecosystem Stress: 10 NTU Threshold

No natural environment is stress-free. Even in pristine watersheds of north coastal California, winter storms generate turbidities that can negatively affect aquatic plants and animals. The ecological significance of low-level turbidities, up to 10 NTU, will depend on the duration of exposure. ODEQ (2004) provides an excellent literature review of turbidity and suspended sediment effects on stream biota and anadromous salmonids. The following effects/responses are included: 1) >= 10 NTU: salmonid reactive distance is decreased by approximately 0.5 with potential change to active feeding strategy (Table 7 and Figure 5 in ODEQ 2004), 2) >= median 10 NTU: steep reduction in BMI densities (Figure 6 in ODEQ 2004), and 3) >= median 10 NTU: steep reduction in periphyton productivity (Figure 9 in ODEQ 2004). Many eastern US states consider 10 NTU the upper cutoff for "trout" streams (e.g., North Carolina). Also in the eastern US, Waters et al. (2001) identify a 10 NTU threshold for fish biotic integrity in 30 Piedmont streams. While 1) and 3) are directly attributable to the magnitude of turbidity, the other effects are a product of magnitude and duration of turbidity. Given the difficulty in assigning ecological effects to daily turbidities less than 10 NTU, we used 10 NTU and greater as a biological threshold for causing background ecological effects. A one-day exceedence of 10 NTU very likely has a net negative effect on overall stream ecosystem productivity by reducing primary and secondary production. However the effect of exceeding 10 NTU for one day would be extremely difficult to measure in the field and would not be significant within the context of an entire water year.

Moderate Stream Ecosystem Stress: 25 NTU Threshold

In the extensive review by ODEQ (2004), the following trends were provided: 1) decreased weight and length of juvenile salmonids (Table 3 in ODEQ 2004), 2) brook trout switch from passive drift feeding to active searching (Table 3 in ODEQ 2004), 3) 13% to 50% reduction in primary productivity (Figure 11 in ODEQ 2004), 4) approaching low asymptote in salmonid reactive distance (Figure 4 and Figure 5 in ODEQ 2004), 5) approaching low asymptote in benthic macroinvertebrate (BMI) densities (Figure 6 in ODEQ 2004), and (6) approaching low asymptote in periphyton productivity (Figure 9 in ODEQ 2004). Berg and Northcote (1985) observed juvenile coho moving closer to the channelbed (within 4 inches), to help maintain their holding position, when exposed to turbidities exceeding 30 NTU. Anderson (1975, p.348) identifies turbidities at 25 NTU and higher as causing significantly greater and more intense impacts to stream biota. Anderson (1975, p. 348): *"In this paper, turbid water is separated from non-turbid water at 27 mg/liter; at 27 mg/liter water has been characterized as "not drinkable," catch of fish drops to one-half, no increased mortality of fish; fish production drops less than 10 percent (Cordon and Kelley)(18)."* We used 25 NTU and greater as a biological threshold for causing much greater effects on overall stream productivity and fish health/behavior, compared to the background productivity effects expected from exceeding the 10 NTU biological threshold.

Severe Stream Ecosystem Stress: 50 NTU Threshold

Bash and Berman (2001) in their literature review found that: 1) juvenile salmonid behavioral changes occur by 60 NTU (Table 2 in Bash and Berman 2001) and 2) juvenile coho can be displaced at 40 to 50 NTU (Table 2 in Bash and Berman 2001). An ongoing laboratory/field study reports that juvenile salmonid feeding remained efficient (amphipods as prey) up to 40 NTU, but that there was almost no feeding by 70 NTU (Cummins and

Madej 2004). Field observations of feeding were curtailed above 40 NTU because juvenile fish were no longer visible. Forced emigration of juvenile salmonids is a severe stressor. Bisson and Bilby (1982) found: *"Juvenile coho salmon (Oncorhynchus kisutch) were subjected to experimentally elevated concentrations of suspended sediment and did not avoid moderate turbidity increases when background levels were low, but exhibited significant avoidance when turbidity exceeded a threshold that was relatively high (> 70 NTU) and was varied according to previous suspended sediment exposure."* We used 50 NTU and greater as a biological threshold for causing much greater effects to overall stream productivity and immediate fish health/behavior changes that threaten fish survival, compared to the background productivity effects expected from exceeding the 10 NTU biological threshold and potential physiological effects to fish and benthic macroinvertebrates from exceeding the 25 NTU biological threshold.

3) Define and Establish Significant "Chronic" Exceedence for Each Biological Turbidity Threshold

A quantifiable definition for 'chronic' was needed to establish significant CWE thresholds. 'Chronic' characterizes an event that occurs much more often than expected, and more often than generally desired. High stream turbidities occur during peak storm runoff when fine sediment is most susceptible to mobilization and delivery into/within the stream channel network. Even though Elder Creek is almost pristine, many days in a wet runoff year will exceed 10 NTU whenever daily average streamflows can easily mobilize and deliver fine sediment. Therefore, the occurrence of many days with turbidities exceeding 10 NTU in a wet year could not be considered chronic. Conversely, daily turbidity rarely exceeds 10 NTU in Elder Creek during baseflows, when there is minimal capability for fine sediment mobilization and delivery. The occurrence of many days in a dry water year exceeding 10 NTU would be considered chronic. Annual hydrographs, revealing a watershed's capability and likelihood for generating, mobilizing, and delivering fine sediment, can be used to quantify and assess 'chronic' conditions as objectively as possible. We used Elder Creek as an example of how hydrographs, sediment delivery, and turbidity can be synthesized for other Northern California streams to quantify CWEs.

To assess 'chronic', runoff processes and stream channel processes in Elder Creek watershed were associated with specific portions of the annual hydrograph. Dunne and Leopold (1978, p. 256 Figure 9-1) identify four pathways for water moving downhill: 1) overland flow, 2) groundwater flow, 3) shallow subsurface stormflow, and 4) saturated overland flow (direct precipitation on the saturated area plus infiltrated water that returns to the ground surface). These also serve as potential fine sediment pathways into the mainstem channel, leaving fine sediment generated within the channel or from the stream banks as other fine sediment pathways.

Overland flow, the most capable pathway for delivering fine sediment to stream channels, was unusual even during intense sustained rainfall that generated the highest runoff peaks (greater than 400 cfs). Shallow subsurface stormflow, often evident as piping flows, occurred during much of the peak runoff period though sometimes lasting (trickling) until approximately 120 cfs to 100 cfs afterwards. During larger peak flows (approximately 200 cfs and greater), piping discharges to the mainstem were noticeably turbid. Small tributary (0.15 mi^2 to 0.5 mi^2) streamflows declined sharply when mainstem streamflows dropped below 60 cfs to 35 cfs. Small tributary flows were likely the result of rapidly declining subsurface stormflow other than piping, as well as from saturated overland flow appearing in small swales. During entire storm runoff recession periods approaching baseflows, streamflow from the tributaries appeared less turbid than mainstem flows.

Fine sediment also can be generated by bank erosion, general channelbed mobility, and mobilization of fine-grained depositional features such as eddy deposits. Based on our field experiences, we associated two physical processes with the annual hydrograph. First, alluvial features deposited by storm events in Elder Creek begin to be inundated at approximately the 10% exceedence streamflow. With greater inundation, the opportunity to mobilize fine sediment improves. USGS field notes record no sand movement until 60 cfs to 70 cfs (Trush 1990). Second, gravel bed surface mobilization began at the 4% annual exceedence streamflow and greater (approximately 200 cfs and greater). Bank erosion was observed at streamflows as low as 100 cfs, but most bank erosion was observed during the highest peaks (greater than 400 cfs) or shortly afterwards during rapidly receding storm flows. Therefore, pathways for fine sediment entering the mainstem channel were extremely limited at streamflows less than 150 cfs to 100 cfs from the Elder Creek watershed. Likewise, fine sediment processes originating within the mainstem channel and its banks were also very limited. Only during higher storm flows, generally above 200 cfs, did the opportunity appear to increase significantly. Figure 26 summarizes these field observations for a typical water year in Elder Creek.

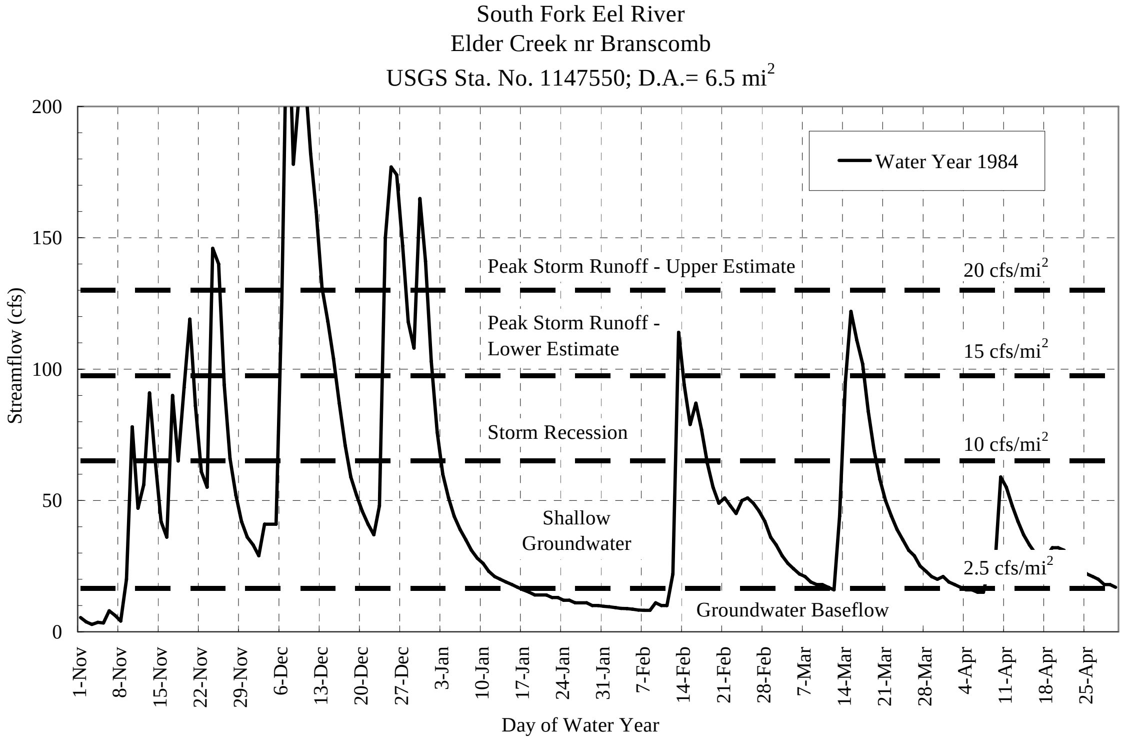


Figure 26. Daily average streamflows in Elder Creek from November 01 to May 01 in WY1984 with flow thresholds for fine sediment delivery into the mainstem channel.

Suspended sediment delivery into mainstem Elder Creek channel at streamflows less than 16 cfs (i.e., at baseflows in Figure 26) near its confluence with the South Fork Eel River is essentially nonexistent. There is no water sheeting across the ground surface. There is no detectable shallow groundwater storm retention feeding the subsurface piping system; tributaries less than 0.5 mi^2 are wet but not flowing. The only fine sediment source, in this pristine watershed during baseflow, is the bed and banks of the mainstem channel network itself. Any mainstem storage of fine sediment that is readily mobilized at these low streamflows is quickly depleted. Not surprisingly in other pristine and old second-growth third order watersheds, not just for Elder Creek, 10 NTU is extremely uncommon at streamflows less than the mean annual flow, such as Elder Creek's 16 cfs baseflow. The mean annual streamflow for Elder Creek is 27 cfs (approximately p = 24% on the annual daily average flow duration curve). USGS suspended sediment data from Elder Creek (Figure 27) show that daily average streamflows equal to or less than 16 cfs (approximately 2.5 cfs/mi^2) exhibit suspended sediment concentrations rarely exceeding 10 mg/l and having a lower bound concentration of < 1 mg/l (below limits of detection).

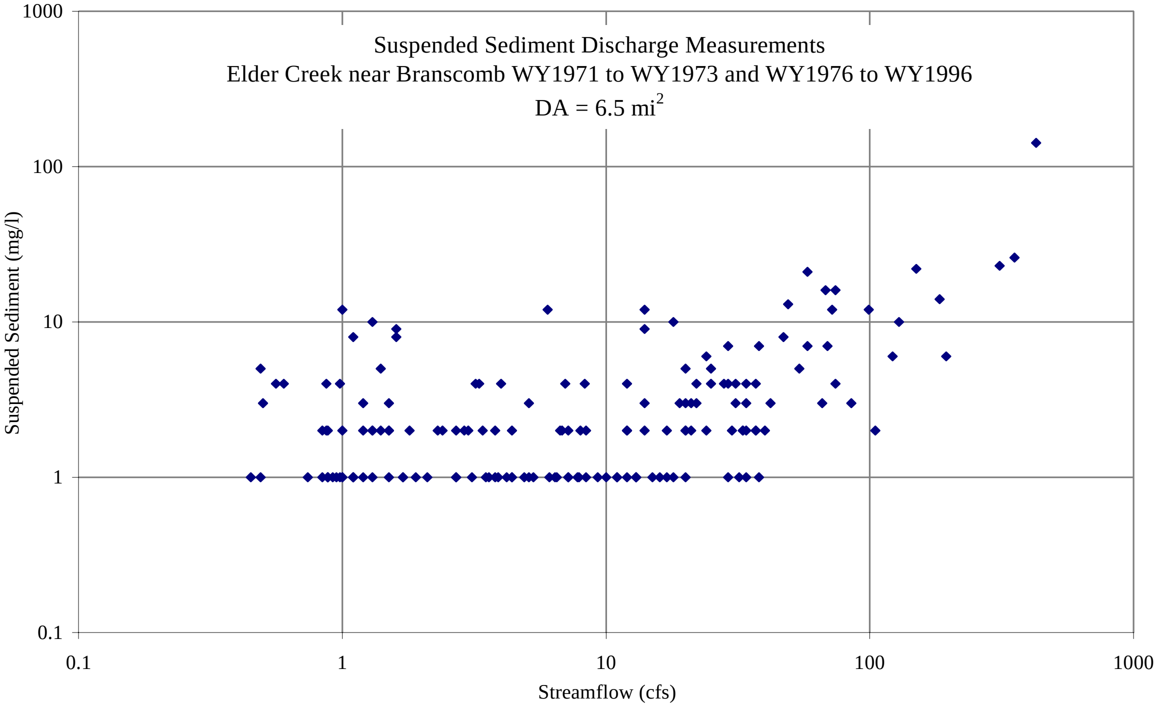


Figure 27. Suspended sediment concentrations and streamflows sampled at the USGS Gaging Station No. 11475560 Elder Creek nr Branscomb WY1971 to WY1973 and WY1976 to WY1996.

'Chronic' relative to the 10 NTU biological threshold was defined as follows: significant CWEs occur when the lower bound NTU at the baseflow transition exceeds 10 NTU. Initially, we assumed 10 mg/l was equivalent to 10 NTU in Elder Creek, a conservative assumption (likely a lower NTU). Subsequently, available NTU data for Elder Creek (Figure 28) verified this assumption. Using these data, the following linear relationship between turbidity and SSC (mg/l) for Elder Creek over an SSC range of 0 mg/l to 30 mg/l was established: NTU = 0.22SSC + 0.16 ($R^2 = 0.77$). The daily averaged flow exceedence probability from WY1991 through WY2005 for the baseflow transition in Elder Creek (i.e., 16 cfs) is p = 55% between November 15 and June 15 (Figure 29). Therefore a significant CWE threshold would be crossed when/if a land use practice (or combination of land uses) generated an annual lower bound turbidigraph resulting in more than 55% of the days between November 15 and June 15 having daily turbidities greater than 10 NTU. This is an extremely conservative CWE threshold given application of the lower bound turbidity. For a stream to exceed this CWE threshold, it must be exceeding the lower bound 10 NTU when there is no detectable surface runoff from the hillsides and roads, as well as during days well past peak rainfall events. Turbidities greater than 10 NTU that persist 10 to 15 days after a peak rainfall event are likely to bridge the next peak rainfall event in Normal and Wet water years, thus offering no (or very little) respite between storms. In Dry water years, even streams with very high fine sediment loading may not exceed this 10 NTU threshold most of the time simply because streamflows are consistently too low to generate and mobilize fine sediment within the third-order stream channel network.

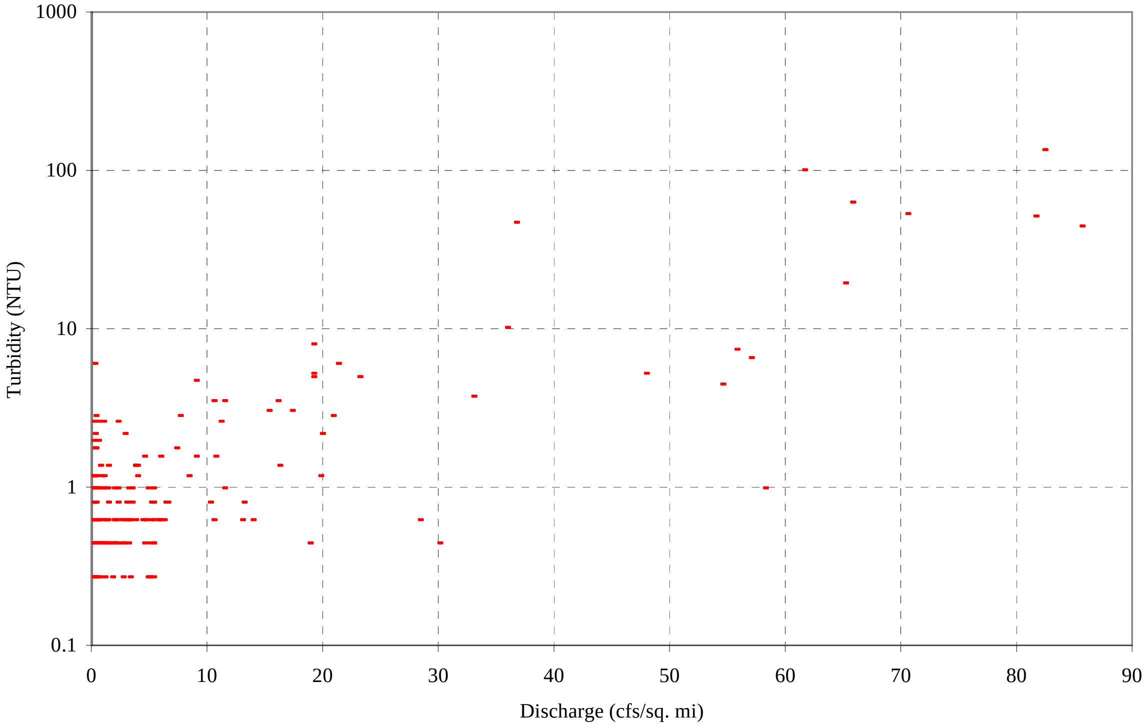


Figure 28. Turbidities and streamflows sampled at the USGS Gaging Station No. 11475560 Elder Creek nr Branscomb WY1971 to WY1973 and WY1976 to WY1996.

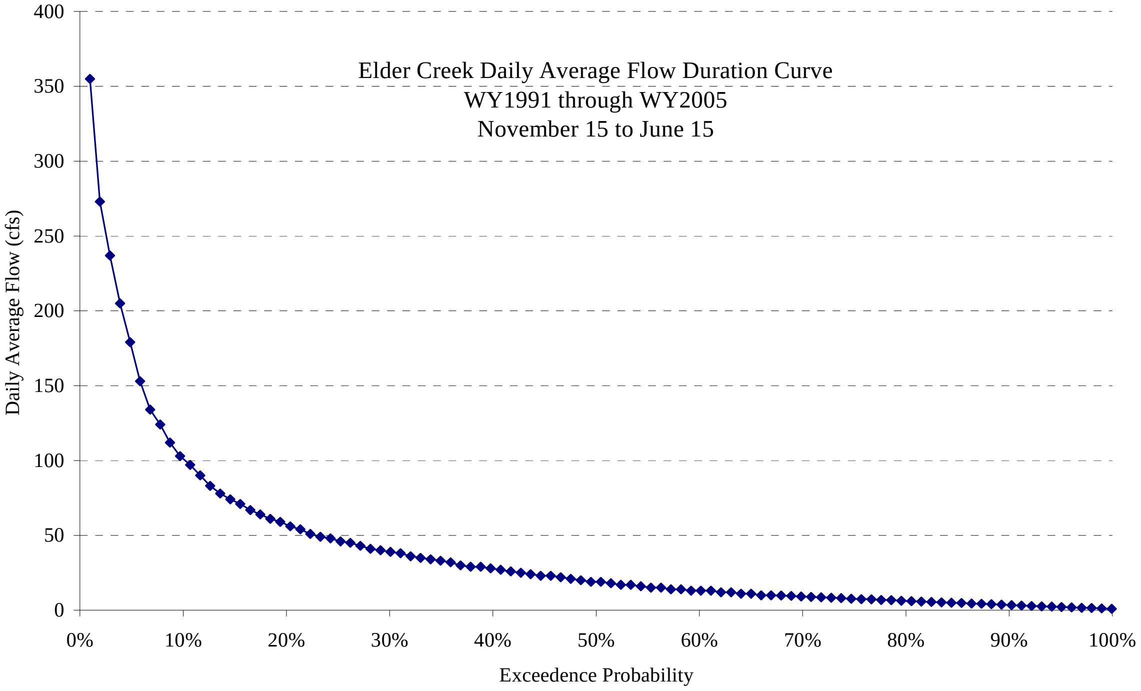


Figure 29. Daily average flow duration curve for Elder Creek from WY1991 through WY2005 between November 15 and June 15.

In pristine and recovered old second-growth North Coastal California third order watersheds, streamflows with turbidities greater than 25 NTU occur almost entirely within peak runoff events. During receding stormflows in Elder Creek, shown as daily average streamflows from 100 cfs (approximately 15 cfs/mi^2) to 120 cfs (approximately 20 cfs/mi^2) down to 60 cfs (approximately 10 cfs/mi^2) in Figure 26, suspended sediment measurements rarely exceeded 25 mg/l or greater than 25 NTU in Elder Creek, especially below the 60 cfs transition from rapid storm runoff to shallow groundwater storm runoff (Figures 27 and 28). The daily averaged flow exceedence probability from WY1991 through WY2005 for 60 cfs (the transition from sustained storm runoff to recession flows) is p = 20% between November 15 and June 15 (Figure 29). ‘Chronic’ relative to the 25 NTU biological threshold was defined as follows: significant CWEs occur when the lower bound NTU for the streamflow at the transition from rapid storm recession runoff to shallow groundwater runoff exceeds 25 NTU. The daily averaged flow exceedence probability from WY1991 through WY2005 for this transition in Elder Creek (i.e., 60 cfs) is p = 20% between November 15 and June 15 (Figure 29). Therefore a significant CWE threshold would be crossed when/if a land use practice (or combination of land uses) generated an annual lower bound turbidigraph resulting in more than 20% of the days between November 15 and June 15 having daily turbidities greater than 25 NTU.

Peak runoff in Elder Creek, above 100 cfs to 120 cfs (Figure 26), generates most suspended sediment delivered to the mainstem channel. The daily averaged flow exceedence probability from WY1991 through WY2005 for a 100 cfs peak runoff in Elder Creek is p = 10% between November 15 and June 15 (Figure 29). During these peakflows, and even the higher storm recession streamflows, turbidities are generally well below 50 NTU (Figure 28). ‘Chronic’ relative to the 50 NTU biological threshold was defined as follows: significant CWEs occur when the lower bound NTU for the streamflow at the transition from peak runoff to rapid storm recession runoff exceeds 50 NTU. Therefore a significant CWE threshold would be crossed when/if a land use practice (or combination of land uses) generated an annual average lower bound turbidigraph resulting in more than 10% of the days between November 15 and June 15 having daily turbidities greater than 50 NTU.

4) Model Lower Bound Turbidity Exceedence Curves as a Function of the Average Annual Timber Harvest Rate

Average annual timber harvest rates ranging from 0% to 6% using the turbidity rating curves in Figure 23 were modeled to identify the rate producing a significant cumulative effect. Exceedences for the three biological turbidity thresholds (10 NTU, 25 NTU, and 50 NTU) as Lower Bound turbidities were plotted: 1) using modeled Lower Bound annual turbidigraphs for each Elder Creek water year from WY1991 through WY2005 (November 15 through June15) and 2) using the averaged modeled annual turbidigraph for the averaged Elder Creek water year between WY1991 to WY2005 (November 15 through June15). On the plot for each modeled water year and harvest rate, the X-axis was the average annual timber harvest rate (CCE 0-15) and the Y-axis was %days that the stated Lower Bound turbidity between November 15 and June 15 was equaled or exceeded.

Results

Lower Bound Turbidity Duration Curves as a Function of the Average Annual Timber Harvest Rate

Lower Bound turbidity duration curves for 10 NTU, 25 NTU, and 50 NTU in WY1991 through WY2005 exhibited similar patterns (Figures 30 through 32 respectively). The 15 widely ranging exceedence curves within each figure, representing the 15 water years modeled, were not a product of random error or experimental error but instead a reflection of how streams naturally vary from year to year. Each figure exhibited two distinct groups of individual yearly curves: Dry years clustered well below the averaged curve and Wet years and most Normal years clustered well above. The averaged water year, if it had actually occurred, would have been a highly unusual hydrological event.

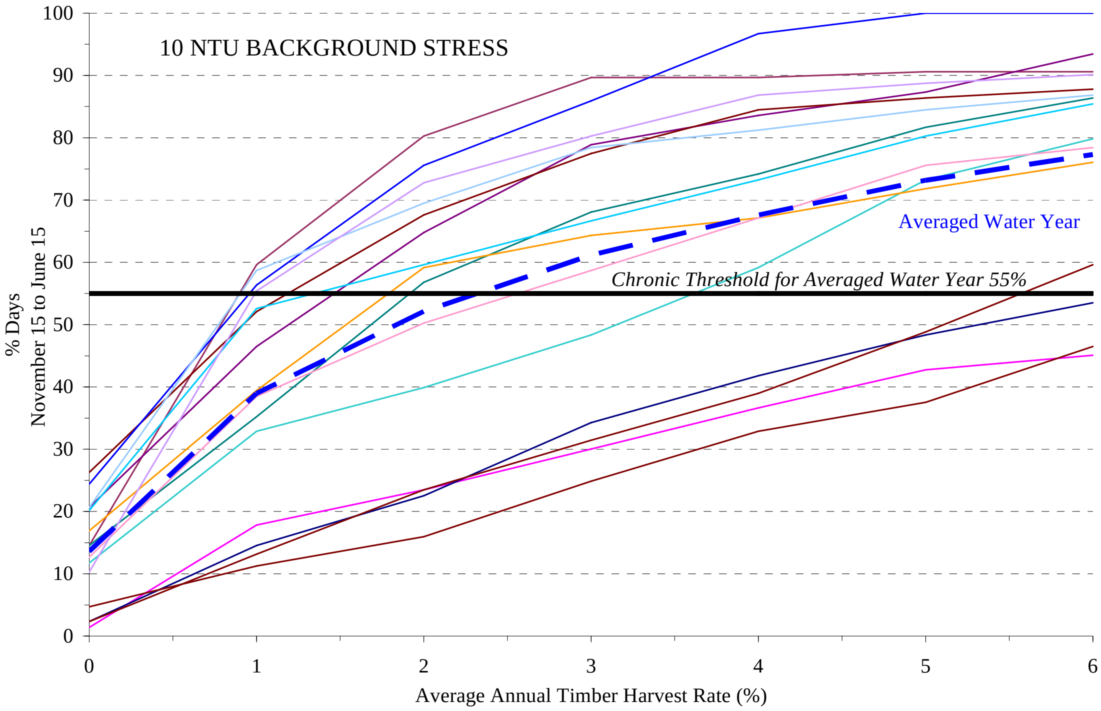


Figure 30. Modeled duration curves as a function of the average annual timber harvest rate (% CCE 0-15) for the 10 NTU Background CWE Threshold from November 15 to June 15 for WY1991 through WY2005.

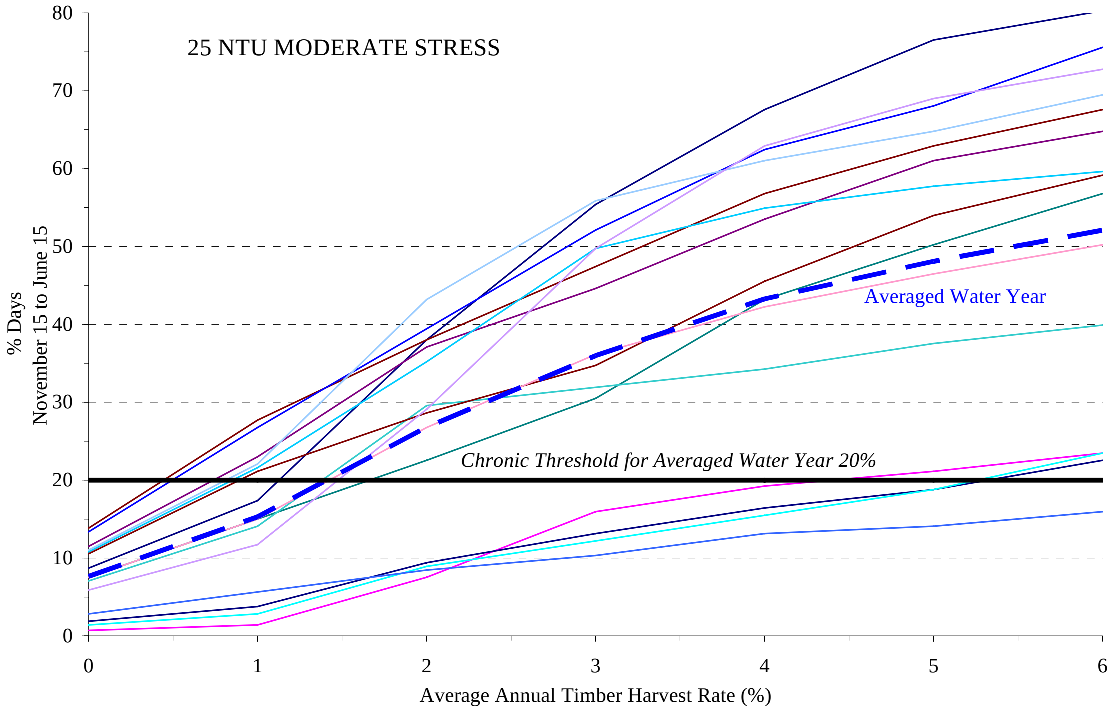


Figure 31. Modeled duration curves as a function of the average annual timber harvest rate (% CCE 0-15) for the 25 NTU Moderate CWE Threshold from November 15 to June 15 for WY1991 through WY2005.

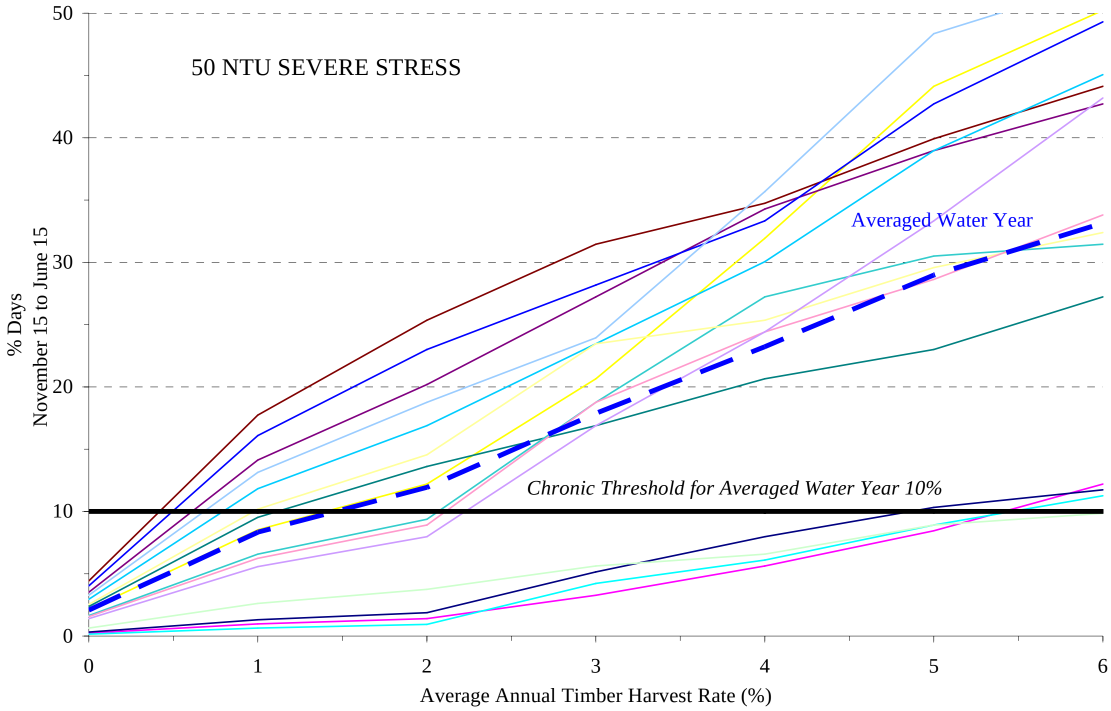


Figure 32. Modeled duration curves as a function of the average annual timber harvest rate (% CCE 0-15) for the 50 NTU Severe CWE Threshold from November 15 to June 15 for WY1991 through WY2005.

Modeled background, moderate, and severe CWEs on anadromous salmonids and the stream ecosystem occurred in the averaged Elder Creek water year from WY1991 through WY2005 at annual average timber harvest rates of 2.3%/yr, 1.4%/yr, and 1.5%/yr (Figures 30 to 32, respectively).

In the averaged water year (WY1991 through WY2005), daily average streamflows of 16 cfs (approximately 2.5 cfs/mi^2) and greater occurred 55% of the days between Nov 15 and June 15 (Figure 29). A 2.3% annual average timber harvest rate in Elder Creek watershed or greater would chronically expose the aquatic ecosystem and anadromous salmonids to background stress or greater, by generating Lower Bound turbidities equal to or greater than 10 NTU whenever daily average streamflow exceeded 2.5 cfs/mi^2, and would be considered a threshold for significant CWEs (Figure 33).

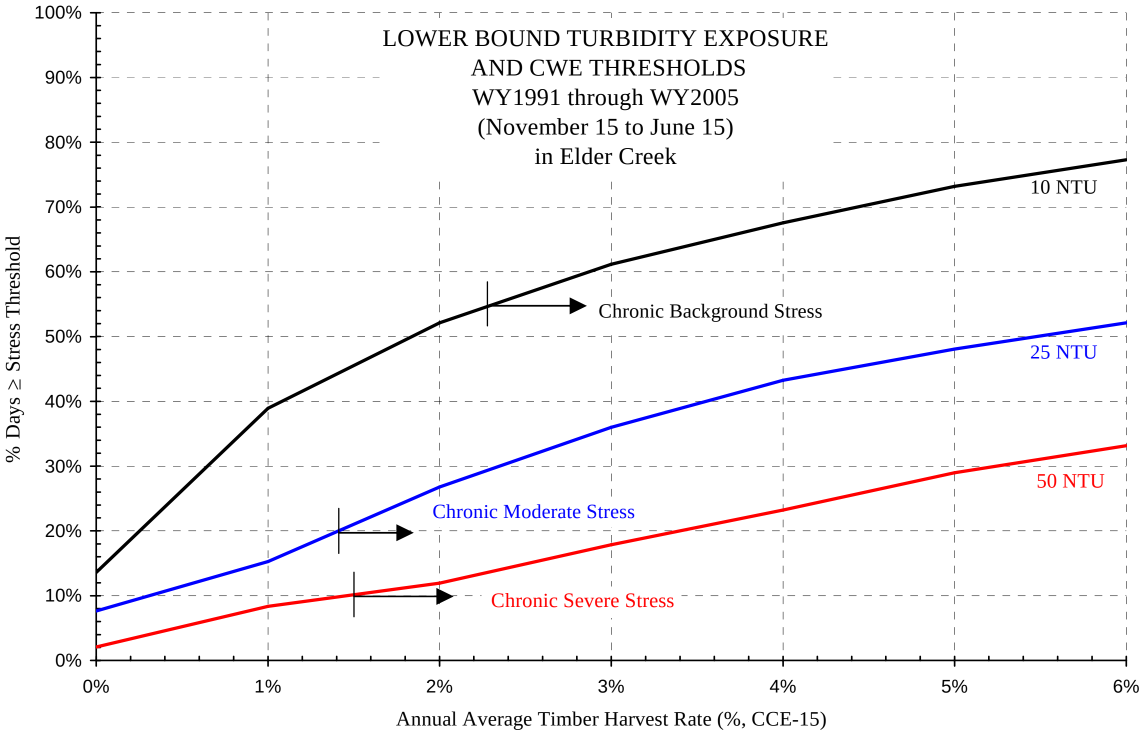


Figure 33. Average annual timber harvest rates at which significant CWEs occur for chronic background, moderate, and severe ecosystem stressors in the averaged water year from WY1991 through WY2005 (November 15 to June 15) in Elder Creek.

Note that even at the 0% harvest rate (computed over the last 15 years) in Figure 33, approximately 14.5% of the days between November 15 and June 15 had Lower Bound turbidities of 10 NTU or greater. Knopp (1993, p.41) found that the differences in fine sediment storage in the stream channels between pristine and old second-growth watersheds were major, concluding that watersheds harvested many years ago, and not since, are still influencing habitat quality today. The 0% lower bound regression was created from pristine and old second-growth streams. In pristine Elder Creek watershed, a lower bound suspended sediment concentration of 10 mg/l would not be attained until reaching 200 cfs and likely higher (Figure 28). On a daily average flow duration curve for WY1991 through WY2005 (for November 15 through June 15), a 200 cfs streamflow has an exceedence of approximately 4% (Figure 29). A 4% exceedence of 10 NTU in Elder Creek, as a Lower Bound turbidity, would be considerably less than the predicted 14.5% exceedence of 10 NTU in the modeled turbidigraph for the 0% average annual timber harvest rate.

For the next higher CWE turbidity threshold of 25 NTU, chronic was defined for streamflows exceeding 60 cfs (approximately 10 cfs/mi^2). The field observations indicated very limited opportunities for fine sediment input from the watershed and only a slightly higher opportunity originating within the channel or from the banks. In the averaged water year (WY1991 through WY2005), daily average streamflows of 60 cfs and greater occurred 20% of the days between Nov 15 and June 15 (Figure 29). The CWE threshold for a Lower Bound turbidity of 25 NTU occurs at an exceedence of 20% in Figure 33 and corresponds to a 1.4% annual average timber harvest rate in the Elder Creek watershed that would chronically expose the aquatic ecosystem and anadromous salmonids to moderate stress (as defined above) and should be considered a significant CWE.

For the highest CWE turbidity threshold of 50 NTU, chronic was defined relative to streamflows exceeding 100 cfs (approximately 15 cfs/mi^2) when runoff and streamflows were most capable of fine sediment mobilization and delivery. A Lower Bound turbidity of 50 NTU likely would not occur on Elder Creek until 400 cfs or higher (Figure 28). In the averaged water year (WY1991 through WY2005), daily average streamflows of 100 cfs and greater occurred 10% of the days between Nov 15 and June 15 (Figure 29). The CWE threshold for a Lower Bound turbidity of 50 NTU occurs at an exceedence of 10% in Figure 33 and corresponds to a 1.5% annual average timber harvest rate in the Elder Creek watershed that would chronically expose the aquatic ecosystem and anadromous salmonids to severe stress and should be considered a significant CWE.

Recommendations

The following methodology for applying CWE thresholds for the averaged water year is proposed for determining significant CWEs for third-order north coastal California watersheds within the regional boundaries of this study:

- <u>Background CWE on Anadromous Salmonid Habitat Capacity and Stream Ecosystem Productivity</u> occurs when 55% of the days between November 15 and June 15 equal or exceed a Lower Bound turbidity threshold of 10 NTU in the averaged water year.

- <u>Moderate CWE on Anadromous Salmonid Habitat Capacity and Stream Ecosystem Productivity</u> occurs when 20% of the days between November 15 and June 15 equal or exceed a Lower Bound turbidity threshold of 25 NTU in the averaged water year.

- <u>Severe CWE on Anadromous Salmonid Habitat Capacity and Stream Ecosystem Productivity</u> occurs when 10% of the days between November 15 and June 15 equal or exceed a Lower Bound turbidity threshold of 50 NTU in the averaged water year.

The specific targets may not be appropriate across the entire north coast region because they are based on applying Lower Bound slope-harvest rate relationships to the Elder Creek example. However, with the data set assembled for this study, the potential exists for developing within-region targets that accommodate north coast variability.

ANALYTICAL STRATEGY NO. 2: MODELING STEELHEAD SMOLT-TO-ADULT RETURN AS A FUNCTION OF THE AVERAGE ANNUAL TIMBER HARVEST RATE

Steelhead in North Coastal California

A healthy watershed must produce a size class distribution and abundance of salmonid smolts to support a returning adult population. Juvenile steelhead may rear in freshwater up to four years or longer before emigrating, though they typically remain 2+ to 3+ years in North Coastal California. Smolt is a term applied to an anadromous juvenile salmonid that is physiologically prepared to adapt to a saltwater existence (Barnhart 1986). During smoltification, several distinct morphological changes occur, including streamlining of the body, development of a silvery appearance, and a loosening of the scales in addition to many physiological adjustments for saltwater tolerance (Zaug and McLain 1972). Size is an important factor governing initiation of smoltification (Hoar 1976). Houston (1961) identified an inflection point in steelhead juvenile length-weight relationships over a narrow range of 165 mm to 175 mm long. Physiological changes occurred within this size range, including much greater resistance to salt water than in smaller or larger individuals. This sharp increase in salinity resistance in the springtime is endogenously cyclical, occurring 3 months prior to smolt transformation (Hoar 1976). Smoltification is reversible: those fish not emigrating will lose their smolt characteristics and saltwater tolerance, and remain in freshwater another year.

Smolts typically emigrate downstream in late-spring in North Coastal California, but a fall outmigration also has been observed (Barnhart 1986). Gradual downstream movement by juveniles may occur during the entire last half of their freshwater lives, not only as smolts. Moffitt and Smith (1950) predict that many steelhead yearlings, 1+ juveniles leaving the headwater regions of the Trinity River near Lewiston, spend a year or longer migrating to the sea and that the size class distribution of the downstream migrants at Lewiston would not be the same as the migrant composition entering the Klamath River or the Pacific Ocean. Taylor’s (1977) detailed study of steelhead outmigration in the Trinity River documents spatial and temporal separation of juvenile size classes. Two distinct size classes of wild steelhead juveniles (80 mm to 100 mm and 150 mm to 170 mm FL were captured at Big Bar weir (70 km below Lewiston Dam) in the main channel from March to June. The 80 mm to 100 mm size class probably represents juveniles just completing their first year. The Weitchpec weir site at the mouth of the Trinity River, 105 km below Big Bar, had a unimodal size distribution of 150 mm to 170 mm FL migrants.

Prevention of cumulative watershed effects to anadromous salmonids requires broader spatial and temporal perspectives than typically addressed in THPs. In part, this is due to the diverse life history demands of anadromous salmonids (Spence et al. 1996). A juvenile steelhead hiding under a pool’s boulder in a tributary 80 miles from the Pacific Ocean will depend on more than one pool’s habitat if it is to have any meaningful chance of returning as an adult. Migrating juvenile Chinook will depend on floodplains, side-channels, and backwaters within large tributaries and mainstem channels to grow their way downstream. Presently turbidity thresholds target water quality in the pool and not water quality in the next 80 miles farther downstream. The implicit justification for not addressing downstream turbidity is that if thresholds can be met upstream (e.g., in the tributary's pool), thresholds are not needed downstream. Another justification is that once this juvenile steelhead successfully rears in its pool, or juvenile Chinook start on their journey, they will migrate directly to the ocean with the mainstem channel functioning simply as a thoroughfare. Neither justification is geomorphically or ecologically valid.

Field observations of steelhead juveniles leaving their natal tributaries and growing their way downstream are important because steelhead smolt survival is strongly a function of fork length upon entering the Pacific Ocean. Added growth can mean greater ocean survival. Field investigations and hatchery brood year survival experiments for releases of varying lengths indicate much higher adult returns for smolts greater than 150 mm to 160 mm (e.g., Kabel and German 1967). Differing productivities, water quality, and lengths of main channel among river basins could have considerable influence on smolt size. The importance of the relationship between the tributary and main channel in determining smolt number and size distribution may be the least appreciated freshwater factor affecting returning adult steelhead populations.

Steelhead and CWEs

Cumulative watershed effects on steelhead also can be quantified. This report examines only the consequence of shifting the smolt size class distribution to the left by modeling stream turbidity effects on smolt size, and ignores reduced habitat capacity effects on smolt numbers. Two key linkages were needed to do the analysis: (a) estimate annual turbidigraphs as a function of the annual average timber harvest rate and (b) estimate reduced specific daily growth rate (and ultimately smolt size) as a function of daily average stream turbidity. The 'conceptual' pathway is straightforward: greater harvest rates generate more turbidity that inhibits growth and results in smaller smolts having less chance of returning as adults. While straightforward, the devil is in the details (and assumptions).

Steelhead are highly adaptable to change. Ward (2006) notes:

> *"Steelhead, unlike salmon, have a highly diverse life history with greater variation in the number of years spent in both freshwater (1 to 5 yrs) and saltwater (1 to 3 yrs), and the ability to spawn repeatedly (usually 10% to 20% of returns are repeats, but it has been higher recently). Steelhead adults return in lower numbers than salmon and over a broader time frame, to spawn in the spring rather than the fall. Survival from egg to fry is higher than salmon, in general. They rear for several years in freshwater, with variation in age structure within and among rivers dependent on the available food and space for these territorial animals. In other words, the carrying capacity for smolt production reaches an asymptote once available rearing space for a given level of production in freshwater has been reached (Fig. 2). Most importantly, a failed year class, due to flood or drought, or poor return of a brood, is quickly made up for by younger and older age classes, such that the age class variation of smolts from a brood may be high, but the total number of smolts remains reasonably constant for a regime of*

> *production. Steelhead have overlapping generations, thus reducing the risk of a catastrophic event, compared to the presence of a single year class of low numbers, or compared to the more defined, non-overlapping generations in salmon."*

Smolts are affected by natural and man-made environmental disturbances that affect their number and size. Man-made cumulative impacts may force the smolt size class distribution farther to the left (i.e., produce smaller smolts) more often than under natural conditions, as well as produce fewer smolts thus forcing the smolt size class distribution downward, especially within the larger size classes (Figure 34). The left-shift and/or diminishment of the smolt size class distribution lowers the probability of achieving an adult escapement once attainable by a size class distribution of smolts influenced only by natural impacts. This left and downward shift eventually, if man-induced impacts increase in severity and/or duration, reduces the probability of sustaining that species population in a given watershed.

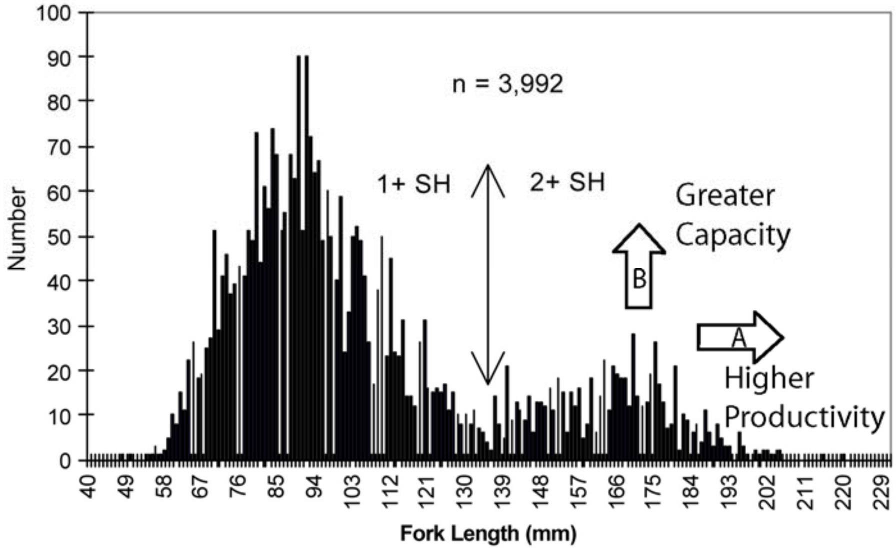


Figure 34. Possible management strategies for increasing steelhead returns: (A) shifting the size class distribution of potential smolts to the right (higher productivity) and (B) shifting the size class distribution of smolts upward (greater habitat capacity).

<u>Goal of Second Analytical Strategy</u>

This second analytical strategy models adult steelhead return as a function of the average annual timber harvest rate by computing differences in smolt-to-adult return (SAR) attributed solely to turbidity effects on juvenile growth. The effect of progressively higher annual timber harvest rates on returning adult steelhead was modeled for Elder Creek to demonstrate how this second analytical strategy can be applied in North Coastal California watersheds.

Methods

This strategy required several steps:

1) Construct lower bound turbidigraphs from November 15 through June 15 for WY1991 through WY2005 under different timber harvest rates for Elder Creek using the Lower Bound turbidity rating curves in Figure 23;
2) Adopt a smolt-to-adult return (SAR) curve for steelhead from the scientific literature;
3) Develop a quantitative relationship between reactive distance and specific growth rate derived from the scientific literature;
4) Model changes in Elder Creek's steelhead adult return as a function of the average annual rate of timber harvest.

1) Construct Lower Bound Turbidigraphs

These turbidigraphs already were computed for the first strategy.

2) Adopt a Steelhead Smolt-to-Adult Return (SAR) Curve

Smolt survival is measured as the probability of returning as a spawning adult (smolt-to-returning adult or SAR). Smolt survival can be documented by: 1) marking individual smolts then capturing them returning as adults, as often done in fish hatcheries, or 2) counting and measuring smolts leaving the watershed while obtaining scales from returning adults to reconstruct their lengths as smolts entering saltwater. The second approach requires an empirical relationship between smolt scale dimension and smolt length. An SAR curve displays the probability of returning as an adult on the Y-axis (the dependent variable) and smolt size (measured as fork length (FL) in mm) on the X-axis (the independent variable). The SAR curve likely changes with annual ocean conditions.

Unfortunately, steelhead SAR curves are uncommon. Using steelhead smolt and adult return data from the Cedar Creek Experimental Hatchery on the South Fork Eel River (Kabel and German 1967), a smolt-to-adult return curve (SAR) was constructed relating steelhead smolt size (FL in mm) to adult return success (% return) (Figure 35). Other steelhead SAR curves for California could be constructed from other field data (e.g., Shapovalov and Taft 1954; Hallock et al. 1961; Bond 2006). Houston (1961) observes that large post-smolts (> 200 mm, but remaining in freshwater) were less efficient in their adaptation to salt water, and possibly more stressed during sea water adaptation, than 'more efficient' smaller smolts 165 mm to 175 mm long. The SAR curve likely levels-off and could drop for very large smolting steelhead.

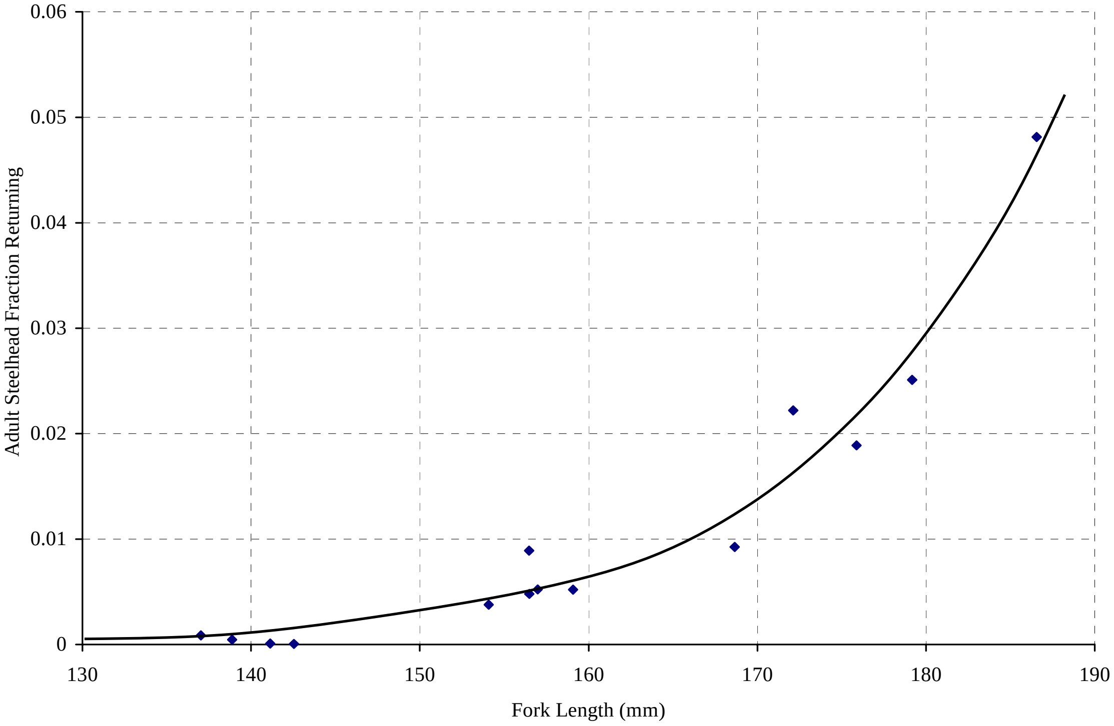


Figure 35. Smolt-to-Adult Return (SAR) curve for steelhead smolts constructed from data provided by Kabel and German (1967).

3) Juvenile Salmonid Growth as a Function of Turbidity

From approximately mid-February through early-June in Northern California, millions of 1+ and 2+ steelhead juveniles migrate toward the Pacific Ocean. As they migrate, they eat. Growth during this time period can be considerable, achieving average specific growth rates of 0.2% FL/day and higher (e.g., Bond 2006; Cannata 1998; Sparkman 2001). Consequently adult return improves if they encounter plenty of food, preferred water temperatures, complex physical habitat for minimizing unnecessary energy expenditure, and good visibility for efficient feeding. At a specific growth rate of 0.2% FL/day and over 100 days (February 15 through May 25), a 150 mm FL 2+ steelhead could grow to 186 mm long. A 150 mm smolt has a 0.5% chance of returning as an adult, whereas a 186 mm smolt has a 4.5% chance (using the SAR curve in Figure 35). To produce one adult steelhead, 200 smolts each 155 mm long would be needed as opposed to 23 smolts each 186 mm long. Benefits of good growth in late-winter through spring growth, therefore, can be highly significant.

One physical factor that can diminish juvenile salmonid growth is turbid streamflow (Newcombe and MacDonald 1991). A critical step in devising a conservative yet realistic CWE model was selection of a quantitative function between turbidity and juvenile salmonid growth. Rosenfeld (2002) reviews quantitative relationships that have been measured for a juvenile salmonid's reactive distance to capturing prey as a function of turbidity. Reactive distance shortened as turbidity increased. Rosenfeld (2002) fits this averaged reactive distance curve to the reviewed studies: PMR = 100 – 44.8 $\log_{10}$ (NTU + 1), where PMR = percent of reactive distance at 0 NTU.

No continuous function has been published, to our knowledge, directly quantifying turbidity effects on juvenile salmonid growth from field data. A consequence of shorter reactive distance would be less efficient foraging (more energy expended per prey captured) and therefore reduced growth. Laboratory and flume studies have demonstrated a negative turbidity effect on growth at discrete turbidities (Henley and others 2000). To estimate daily growth effects from fluctuating turbidity, as occurs in an annual turbidigraph, our model computes daily changes in specific growth rate proportional to Rosenfeld's (2002) relative reactive distance curve (Figure 36). One modification in applying the Rosenfeld equation for estimating juvenile steelhead growth was made.

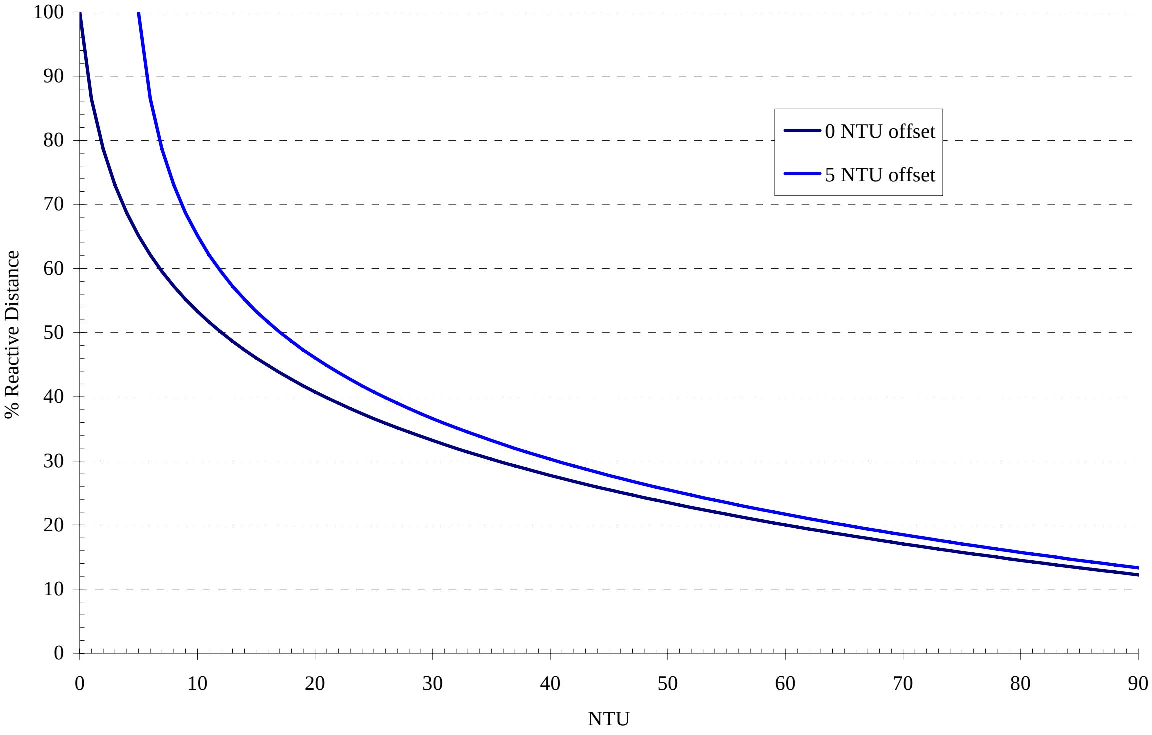


Figure 36. Reactive distance curves as a function of turbidity, with and without a 5 NTU offset.

Reactive distance is highly sensitive to low turbidity. Relative reactive distance at 10 NTU is 53%, and at 5 NTU is 65%. Harvey and Railsback (no date) assumed < 5 NTU did not affect reactive distance to drifting prey (ODEQ 2004). In streams with chronically high NTU, the specific growth rate likely begins dropping at extremely low NTUs (e.g., 5 NTU or lower), whereas in a pristine stream the specific growth rate probably doesn't begin dropping until reaching 10 NTU or higher. This is because all other effects associated with chronic turbidity will also contribute to lowering the specific growth rate (Henley and others 2000) even at very low NTUs (e.g., greater channelbed embeddedness will reduce benthic macroinvertebrate habitat capacity). However our modeling isolated and assessed just one potential effect of high turbidity, and not other related geomorphic effects. For our model, the Rosenfeld reactive distance curve was off-set 5 NTU as in Figure 36, thus the modeled specific growth rate was unaffected by turbidities less than 5 NTU. Though the specific growth rate was significantly reduced (below 30%) in the model at higher turbidities, growth still occurred at 50 NTU and higher.

4) Model Changes in Elder Creek's Adult Steelhead Run as a Function of the Average Annual Timber Harvest Rate

Models are important tools for isolating and assessing those physical independent variables responsible for CWEs. Models can imperfectly isolate, and help evaluate, potential CWEs attributable to elevated stream turbidity by keeping other physical variables uncharacteristically constant. Streams with unnaturally high sediment loads will respond physically by shallowing pools, increasing channel embeddedness, reducing streambed particle size, and increasing channel width (and in so doing, eliminating over-hanging bank cover) to mention only a few physical responses. All these physical variables reduce anadromous salmonid habitat capacity for adult spawning and juvenile rearing (Spence et al. 1996). They also reduce juvenile salmonid growth (Suttle et al. 2004). A field experiment devised to isolate the importance of turbidity would somehow need to prevent/remove cumulative impacts to physical habitat quantity and quality associated with higher turbidity from also contributing, both locally and far downstream. To isolate CWEs attributable to stream turbidity, our model kept these physical factors constant by modeling habitat and population parameters characteristic of healthy stream ecosystems (as in Elder Creek) and anadromous salmonid populations.

The Model

Our simple model attempted to simulate and evaluate (A) while keeping (B) constant in Figure 34. The ultimate dependent variable in this second analytical strategy was smolt-to-adult return: greater harvest rates produce more turbidity that depresses juvenile growth culminating in lower smolt-to-adult return.

Two plausible life history tactics were used to model how the average annual timber harvest rate could impact returning adult steelhead run size in a normal water year (WY1993) on Elder Creek. The first generalized size class distribution of potential juveniles was estimated from summer juvenile steelhead field sampling reported in Connor (1992) and patterned after other field studies (Bond 2006; Environmental Science Associates 2003; Ricker 2003; Sparkman 2001; Vaughn 2000), with the following sizes and number per size class: 120 mm – 50 juveniles, 130 mm – 100 juveniles, 140 mm – 200 juveniles, 150 mm – 300 juveniles, 160 mm – 200 juveniles, 170 mm – 100 juveniles, and 180 mm – 50 juveniles. The number of juveniles and pre-smolts in each size class was configured to collectively represent 1 pre-smolt for every 10 ft of stream channel length. Size class distribution A was modeled for 100 days growth from February 15 through May 25 using Lower Bound turbidigraphs for 0% to 6% average annual timber harvest rates and a daily specific growth rate of 0.2% FL/day. The size class distribution totaled 1000 potential smolts representing the 2 miles of Elder Creek's excellent rearing habitat (i.e., 1 potential smolt every 10.6 ft of channel) (Trush 1991).

To estimate daily growth effects from fluctuating turbidity, as occur in annual turbidigraphs, our model computes daily changes in the specific growth rate proportional to Rosenfeld's relative reactive distance curve (Figure 36). Two model parameters helped define a healthy stream environment for steelhead independent of turbidity: 1) a smolt density of 10 ft/smolt and 2) a maximum specific growth rate of 0.2% FL/day for 1+ and 2+ juveniles (e.g., Bond 2006 and Sparkman 2001).

Growth for each discrete size class of juvenile steelhead (120 mm to 180 mm) was modeled beginning February 15 until May 25. For each daily turbidity value beginning February 15, a decrease in maximum allowable specific growth rate (0.2% FL/day) was computed using the function relating daily growth to turbidity, then applied to estimate a daily increment in fork length. This daily increment was recomputed each day up through May 25. At the end of this growth period, the number of returning adults was estimated from the SAR curve at each average annual timber harvest rate. This first life history tactic example addressed potential impacts to Elder Creek's steelhead population entirely dependent on Elder Creek: the model had the 1000 juveniles grow 100 days in lower Elder Creek and smoltify, then directly enter the Pacific Ocean on May 25, thus circumventing the need to migrate 80 miles down the Eel River mainstems and estuary.

A second hypothetical life history tactic, a size class distribution of 1000 potential smolts, initially larger than the previous juvenile size class distribution, was modeled for 50 days (also ending May 25), with the following sizes and numbers per size class: 140 mm – 50 smolts, 150 mm – 100 smolts, 160 mm – 200 smolts, 170 mm – 300 smolts, 180 mm – 200 smolts, 190 mm – 100 smolts, and 200 mm – 50 smolts. This second example emphasized the importance of growth once potential smolts leave their natal stream (in this case, Elder Creek) and begin their migration to the Pacific Ocean. The model had these larger pre-smolts leave Elder Creek on April 06 then grow their way downstream for 50 days to the Pacific Ocean influenced by the same turbidigraph used in the first life history tactic.

In isolating the potential effect of turbidity on SAR, the model assumed: 1) no change in survival of other life history stages, 2) no change in physical habitat quality or quantity, 3) no change in food availability (e.g., benthic macroinvertebrate drift rate), and 4) no water temperature effects attributable to the average annual timber harvest rate. Omission of these important habitat parameters steered our model toward a highly conservative outcome, i.e., the actual CWEs are greater. Higher turbidity indicates other sediment-related effects on steelhead habitat that would decrease the carrying capacity at each life stage and degrade habitat quality. The model also assumes direct relationships between 1) reactive distance and feeding efficiency, and 2) feeding efficiency and growth. In all likelihood, the decline in feeding efficiency (with increasing NTUs) is greater than the decline in reactive distance in the wild at higher NTUs (> 20 NTU) because prey abundance is also impacted by higher turbidity (and associated physical responses of the streambed to greater fine sediment load, e.g., embeddedness). Fewer benthic macroinvertebrate prey would increase foraging energy expenditure even more.

Results

Change in Smolt Size and SAR as a Function of the Average Annual Rate of Timber Harvest

The average annual timber harvest rate had an important effect on modeled growth of a 150 mm FL juvenile steelhead (Figure 37). After 100 days of modeled growth using the WY1993 turbidigraph (a typical runoff year), juveniles attained a 171 mm FL with a 0% average annual timber harvest rate and slightly more than 160 mm FL with a 2% average annual timber harvest rate (CCE 0-15, labeled ‘CCE’ in Fig. 37). While 171 mm juveniles were only 6.3% longer than the 160 mm juveniles, their predicted smolt-to-adult returns (Figure 35) were 0.63% for 160 mm and 1.49% for 171 mm. A 171 mm smolt is over twice as likely to return as an adult than a 160 mm smolt.

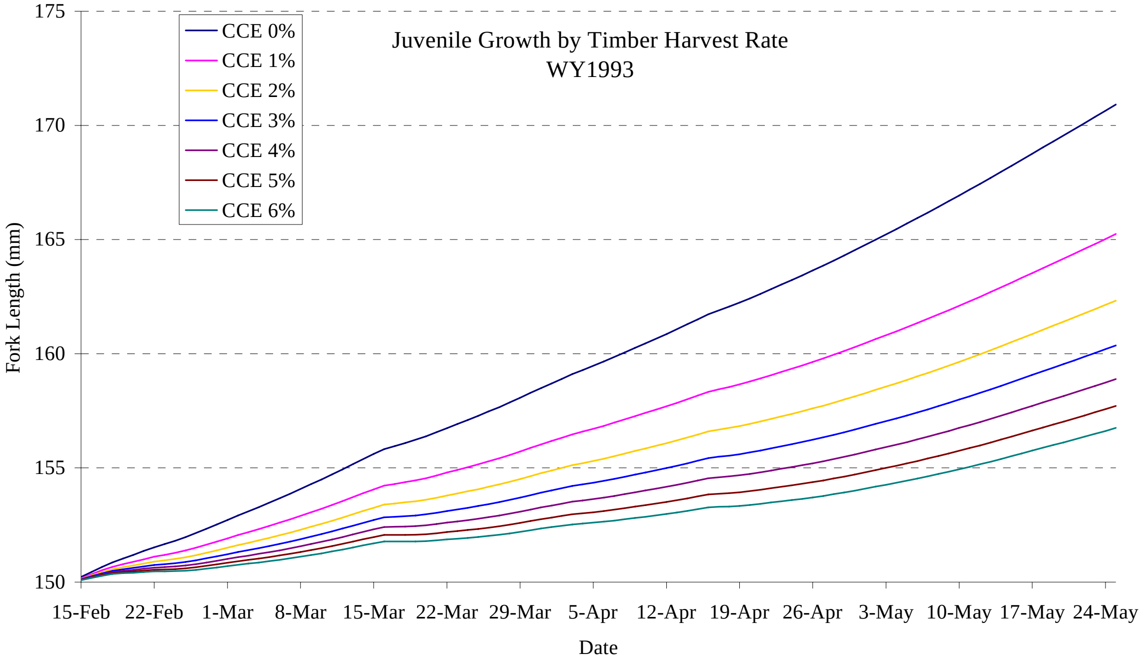


Figure 37. Modeled juvenile steelhead growth as a function of average annual timber harvest rate in WY1993 for a 150 mm juvenile beginning February 15 and ending May 25.

Predicted Adult Steelhead Return as a Function of the Average Annual Rate of Timber Harvest

Modeled steelhead adult returns for the first size class distribution sharply dropped with increasing average annual timber harvest rates (Table 11). For the juveniles entering the Pacific Ocean with no additional growth, the estimated adult return was 5 adults (Table 11), compared to 39 adults with 100 days additional growth in Elder Creek under a 0% average annual timber harvest rate. By the 2% average annual timber harvest rate, Elder Creek’s SAR potential decreased over half (58% $\%\text{Loss}_{0\%}$ in Table 11) to 16 adults, or 8 adults/mile. Above the 2% harvest rate, predicted adult return continued declining but only gradually, reaching a 75% decline by the 6% average annual timber harvest rate. The decline from

‘ALL’ and 0% adult return of 16% (Table 11) reflects the difference between pristine conditions and old second-growth conditions.

Table 11. Predicted steelhead adult return modeled for 1000 juveniles growing 100 days beginning February 15 in 2 miles of lower mainstem Elder Creek under the WY1993 Elder Creek turbidigraph for 0% to 6% average annual timber harvest rates.

			Average Annual Timber Harvest Rates (CCE 0-15)						
	NG	All	0%	1%	2%	3%	4%	5%	6%
Return	5	46	39	22	16	14	12	11	10
%Loss_{all}	---	0	16	51	65	71	73	76	79
%$\text{Loss}_{0\%}$	---	---	0	42	58	65	68	72	75
SAR (%)	0.53	4.59	3.87	2.23	1.62	1.35	1.22	1.09	0.97

Note: “NG” is no additional growth in the initial juvenile size class distribution and ‘ALL’ is 50 days with NTU < 5.

Modeled steelhead adult returns for the second size class distribution also dropped with increasing average annual timber harvest rates (Table 12) but not as sharply. Pre-smolts were already above the 160 mm to 170 mm FL range for having significantly higher smolt-to-adult return. With no additional growth, the model predicted an adult return of 22 adults. Additional growth over 50 days was still important. Under a 0% harvest rate, the model predicted a return of 83 adult steelhead.

Table 12. Predicted steelhead adult return modeled for 1000 juveniles growing 50 days after leaving Elder Creek and migrating to the Pacific Ocean beginning April 06 under the WY1993 Elder Creek turbidigraph for 0% to 6% average annual timber harvest rates.

			Average Annual Timber Harvest Rates						
	NG	All	0%	1%	2%	3%	4%	5%	6%
Return	22.2	90.2	83.1	62.8	50.7	45.6	41.7	38.3	35.5
%Loss_{all}	---	0	7.9	30	44	50	54	58	61
%$\text{Loss}_{0\%}$	---	---	0	24	40	45	50	54	57
SAR (%)	2.22	9.02	8.31	6.28	5.07	4.56	4.17	3.83	3.55

Note: “NG” is no additional growth in the initial juvenile size class distribution and ‘ALL’ is 50 days with NTU < 5.

The actual size class distribution of potential smolts annually leaving Elder Creek has never been measured, but likely falls between the two size class distributions. Under ‘ALL’ in Table 12 (modeled as optimal growth over 50 days), the predicted adult return of 90.2 adults for 2 miles of stream channel and an SAR of 9.02% would be high.

Discussion

An almost exponential steelhead smolt survival curve between 120 mm and 190 mm and a steeply declining growth curve between 5 NTU and 70 NTU contributed to our conservative model's forecast: annual average timber harvest rates (measured as CCE 0-15) of 1.5% to 2.2% can begin to cause significant CWEs to the stream ecosystem and anadromous salmonids. Our turbidity analysis did not distinguish historic residual sediment sources from those generated recently. Perhaps contemporary effects from annual harvest rates of 1% and 2% would not be as great when applied to watersheds never harvested before. However most of today's timber harvest areas have been harvested at least once before. Our 0% annual average harvest rate, calculated from the last 15 years, reflects that legacy: chronic effects modeled between 0% and 2% annual average harvest rates increased sharply. Our study was not designed to distinguish one sediment source from another, either spatially or historically. Whether 10%, 30%, or 70% of a 2005 annual turbidigraph from a third-order watershed harvested in 2003 is the consequence of former logging, it would not change the impacts of today's CWEs and the stream ecosystem and fish.

A Watershed's Intrinsic Sustainable Population (WISP)

A Watershed's Intrinsic Supportable Populations (WISP) is the long-term returning anadromous salmonid adult population attributable to smolts reared entirely within the watershed. The modifier 'long-term' is necessary to account for inter-annual variation in pre-smolt and smolt production within the watershed, as well as under ocean conditions. There is no one 'supportable' or sustainable threshold steelhead population size for a watershed, but rather a naturally occurring range. Inter-annual population variation can be quantitatively estimated by modeling cohort changes in rearing density and size class distribution (both reflecting changing annual pre-smolt (2+ juveniles and larger 1+ juveniles) and smolt production) and smolt-to-adult return (SAR) (reflecting changing annual ocean conditions). Importantly, WISP excludes any population benefit accrued outside the watershed's boundary. For example, once steelhead smolts and pre-smolts leave Elder Creek (a 6.5 mi^2 watershed in the upper South Fork Eel sub-basin) and begin their 80 mile migration downstream, they can continue growing in a productive riverine and/or estuarine environment. Growth during migration will improve their likelihood of returning as adults. Other factors might not (e.g., pikeminnow predation reducing their number or high turbidity and water temperatures impairing added growth). The observed adult steelhead population annually returning is an outcome of: 1) the habitat capacity and productivity of the natal watershed itself (therefore, use of the modifier 'intrinsic'), 2) environmental conditions in the remainder of the river basin, 3) ocean survival, and 4) adult upstream migration survival. As the natal watershed in question becomes bigger, i.e., becomes a greater percentage of the basin area, the WISP steelhead population size merges with the Basin's population size. In our analysis using Elder Creek as an example, the WISP of a third-order watershed was analyzed as part of a much larger river basin.

Another way of conceptualizing WISP is to "cut-out and transport" the entire Elder Creek watershed unscathed to the Pacific Ocean's edge, thus eliminating the pre-smolts and smolts' need to migrate down 80 miles of mainstem Eel River and through the estuary. Elder

Creek's smolts, now directly entering the ocean instead, would produce fewer returning steelhead adults because they could not benefit from added growth accrued during mainstem and estuary migration. The number of adult steelhead returning under this scenario over the long-term would be Elder Creek watershed's intrinsic supportable population or WISP.

Elder Creek's WISP, under median environmental conditions, was calculated as: 1 pre-smolt/10 ft * 2 miles rearing habitat * 5280 ft/mi * 0.025 SAR = 26 adults. Other values for pre-smolt rearing density and SAR can be modeled to estimate good cohort years and poor cohort years, to establish a range in annual adult run size. Trush (1991) observed annual runs in the 1980's (before the pikeminnow invaded the South Fork Eel River) between 50 and 80 adult steelhead. Roughly half or more of these adult steelhead may have returned because of net benefits accrued to them as outmigrating smolts and pre-smolts (primarily added growth) after they left their natal Elder Creek watershed. The discrepancy, between 26 adults and 50 to 80 adults, could result from: 1) poor values for juvenile rearing density used as a surrogate for estimating smolt number, 2) application of a low SAR curve, 3) overestimation of adult run size, and 4) adult straying during migration.

The WISP concept helps in assigning a discrete cause-effect relationship between timber harvest and anadromous salmonids. CWEs are difficult to evaluate and particularly difficult to assign discrete causes. Watersheds rarely are affected by just one land use and steelhead are affected everywhere they go. The number of returning adult steelhead, as just discussed, depends on many factors within and outside the natal watershed. In evaluating CWEs, we attempted to isolate the potential (modeled) effect of turbidity (caused by land uses within the watershed) on the watershed's capability for producing adult steelhead (WISP), and exclude many other potential cumulative effects originating within the river basin and in the Pacific Ocean.

The WISP concept allows that a watershed could have a highly degraded capability, but still have a sizable adult run if other relatively healthier parts of the river basin, particularly an estuary, compensate. The opposite circumstance is common in North Coastal California: a few watersheds in the basin remain in good condition for steelhead, but the mainstem channel and estuary are highly degraded. In this situation, a watershed's WISP assumes a much greater role for sustaining future steelhead runs. Given the model results, an average annual timber harvest rate of 2% to 4% could have a substantial effect on adult run size. Mainstem channels of the Eel River and the Eel River estuary are not in good condition. If Elder Creek was logged, what minimum WISP must be maintained to expect Elder Creek watershed to sustain an annual steelhead run?

'Maintain' would entail saturating Elder Creek with enough eggs that would survive to fully stock Elder Creek's 2 mile mainstem channel rearing capacity with older juveniles (i.e., make 2+ rearing habitat the limiting factor and not the number of emergent fry or 1+ juveniles). To achieve 1 smolt/10 ft of channel, approximately 52,800 eggs would be required (assuming an egg-to-survival rate of 2%). Using 5000 eggs/female, approximately 20 adults (1:1 male/female ratio) would be needed, or a 10 adults/mile return. Our model for the first plausible life history tactic of rearing 100 days in mainstem Elder Creek essentially is WISP. An adult return/mile greater than 10 occurs between the 1% and 2% average annual average timber harvest rates in Table 11 (showing adult steelhead return for 2 miles of channel). For the second size class distribution, a 10 adult/mile return occurs with no added growth. The high adult returns at even 5% and 6% average annual timber harvest rates demonstrate that added modest mainstem/estuarine growth for pre-smolts leaving a very healthy watershed could be highly significant.

The adult steelhead population in a third-order stream channel in North Coastal California with a WISP hovering at, or less than, 10 adults/mile would likely continue declining if the mainstem channel and estuary were providing no benefit. As a stream's habitat capacity and productivity decline, fewer adults would be needed to saturate the stream with enough eggs to fully stock the impaired juvenile rearing capacity. WISP would therefore decline. However, the decline cannot continue indefinitely. Eventually, at some threshold WISP, stochastic environmental events (e.g., a late-winter flood scours away all redds) would begin to exert control. Maintaining the juvenile rearing capacity would not guarantee recovery from stochastic events but would be one prominent strategy for doing so (refer to McElhany et al. 2000).

This threshold, marking a WISP where the adult run is seriously jeopardized, could be a very low adult/mile return. Ward (2006) notes:

> *"Steelhead populations are very productive at low spawner abundance, where there is little or no density-dependent competition for food and space by juveniles. At the Keogh River, the capacity for smolt yield during the 1980s regime was approximately 6,500 smolts (Ward and Slaney 1988; Ward 1996), and we noted that a few hundred spawners could almost achieve that level of production (Fig. 2). For example, if the population were reduced by some catastrophic event to 10% of its carrying capacity (the conservation concern zone; Fig. 1), or 100 adults at the Keogh River, it would very quickly rebuild naturally, in theory to 60% of capacity in one generation, and almost to its full capacity within the next generation. The latter is dependent on the conditions for smolt-to-adult survival."*

Ten percent of 10 adults/mile is only 1 adult/mile. However Ward's observed adult returns include the entire basin's capacity for adult return, not only the WISP. McElhany et al. (2006) conditionally (almost reluctantly) recommend a minimum population size of 4 adults per mile. This also seems a very low number. Again, McElhany et al. (2006) were not separating adult return by WISP and the entire basin. One pair of river otters cruising Elder Creek can easily wreak havoc with this number. Nevertheless, a second WISP adult steelhead population threshold, differentiating minimum supportable population from one seriously threatened, could be established at 4 returning adult steelhead per mile of third-order stream channel. However, the eggs from 2 females could not fully stock Elder Creek to 1 pre-smolt/10 ft of channel.

These two adult steelhead population thresholds are relevant to our CWE analysis. The first is a threshold of 10 adults/mile, where fewer adults/mile lead to long-term population decline (i.e., would be considered impaired and vulnerable). A second threshold of 4 adults/mile transitions from an impaired watershed to one seriously threatened (i.e., unsustainable).

Both thresholds do not account for benefits accrued outside the natal watershed. Potential CWEs from timber harvest within the watershed can be evaluated without addressing potential CWEs throughout the entire river basin. For example, a watershed may have a steelhead run size of 8 adults/mile, but 5 of these adults required the basin's mainstem and estuary for added growth otherwise they never would have returned. This watershed would appear to be close to the 10 adults/mile threshold, but actually it would be less at 3 adults/mile (the 8 minus the 5 needing downstream rearing). Significant CWEs could be occurring in this watershed, but the basin would be compensating for them. Distinguishing those adults requiring outside help (5 adults/mile in this example) and those that do not (3 adults/mile) would require considerable fieldwork. Possibly, adult scales can be interpreted to reconstruct the life history tactics of individual 'successful' adults for individual watersheds (i.e., those returning to spawn). A more practical approach would be to improve the SAR curve and develop 'healthy' smolt or pre-smolt size class distributions. Such an approach would be region-specific. Farther south along the west coast, WISP very likely declines naturally (because of an even less favorable annual hydrology), while the annual adult run likely becomes even more dependent on the lower mainstem, and particularly estuary, for critical juvenile and smolt rearing.

The two thresholds, 10 adults/mile and 4 adults/mile, were evaluated for potential timber harvest effects on steelhead populations. Referring back to Table 11 for the model results using 100 days growth in Elder Creek during a Normal WY1993, the 10 adults/mile threshold was not exceeded between average annual timber harvest rates of 1.5% and 2.0%, while the 4 adults/mile threshold was not exceeded by the 6% average annual timber harvest rate.

Recommendations

Recommendation No. 1. The following methodology for applying CWE thresholds for the averaged water year is proposed for determining significant CWEs for third-order North Coastal California watersheds within the regional boundaries of this study:

- Background CWE on Anadromous Salmonid Habitat Capacity and Stream Ecosystem Productivity occurs when 55% of the days between November 15 and June 15 equal or exceed a Lower Bound turbidity threshold of 10 NTU in the averaged water year.

- Moderate CWE on Anadromous Salmonid Habitat Capacity and Stream Ecosystem Productivity occurs when 20% of the days between November 15 and June 15 equal or exceed a Lower Bound turbidity threshold of 25 NTU in the averaged water year.

- Severe CWE on Anadromous Salmonid Habitat Capacity and Stream Ecosystem Productivity occurs when 10% of the days between November 15 and June 15 equal or exceed a Lower Bound turbidity threshold of 50 NTU in the averaged water year.

The specific targets may not be appropriate across the entire north coast region because they are based on applying Lower Bound slope-harvest rate relationships to the Elder Creek example. However, with the data set assembled for this study, the potential exists for developing within-region targets that accommodate North Coast variability. If one CWE threshold is exceeded the other two are typically exceeded as well; all CWE thresholds are more likely to be exceeded in wet water years than dry.

Recommendation No. 2. Our modeled turbidity biological analyses indicated that an average annual timber harvest rate, measured as CCE 0-15, between 1.4%/yr and 2.3%/yr could cause significant CWEs to the stream ecosystem and anadromous salmonids. Annual average harvest rates above 1.4% in planning watersheds should be reason for heightened scrutiny of additional harvest proposals and only allowing the most low-impact harvesting (e.g., no clearcutting, tractor yarding or winter operations).

Recommendation No. 3. Old second growth streams are not adequate (i.e., too turbid) for establishing background conditions for steelhead populations, and should not be used for this purpose. Although old second growth streams have turbidities considerably below the CWE thresholds recommended in this report, chronic turbidity effects are still likely occurring.

Recommendation No. 4. Evaluation of potential CWEs from the timber harvest rate should be focused on a watershed's intrinsic supportable population (WISP) for steelhead rather than on total adult run size. The transition to an impaired adult steelhead run population in our third-order watershed (Elder Creek), using 10 adults/mile as the threshold, occurred at an average annual timber harvest rate between 1.5% to 2.0%.

Recommendation No. 5. Development of better and more universal smolt-to-adult return curves (SAR) for North Coast steelhead should become a high priority for assessing CWEs.

Recommendation No. 6. For streamflows greater than approximately 30 cfs/mi^2, apply the SEV protocol of Newcombe and Jensen (1996) assessing acute CWE effects on a continuous hourly time-step.

Literature Cited

Anderson, H.W. 1975. Sedimentation and turbidity hazards in wildlands. Pp. 347-375, in Watershed Management Symposium Proceedings, Irrigation and Drainage Division, Am. Soc. Civil Engineers, New York.

Barnhart, R. 1973. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Southwest) – steelhead. USFW Biol. Rept. 82(11.60). US Army Corps of Engineers TREL-82-4. 21 p.

Bash, J. and C. Berman. 2001. Effects of Turbidity and Suspended Solids on Salmonids. Final Research Report, Research Project T1803, Task 42, Effects of Turbidity on Salmon. Center for Streamside Studies, University of Washington, Seattle, WA 98195. 66 p. with appendices.

Berg, L. and T. G. Northcote. 1985. Changes in territorial, gill-flaring, and feeding-behavior in juvenile coho salmon (Oncorhynchus kisutch) following short-term pulses of suspended sediment. Can. J. Fish. Aqua. Sci. 42(8):1410-1417.

Bisson, P.A. and R.E. Bilby. 1982. Avoidance of suspended sediment by juvenile coho salmon. North American Journal of Fisheries Management 2:371-374.

Bond, M. 2006. Importance of estuarine rearing to central California steelhead (Oncorhynchus mykiss) growth and marine survival. Master Thesis. University of California Santa Cruz. 59 p.

Cannata, S.P. 1998. Observations of steelhead trout (Oncorhynchus mykiss), coho salmon (O. kisutch) and water quality of the Navarro River estuary/lagoon May 1996 to December 1997. Draft Report. Humboldt State University Foundation, April 20, 1998.

Connor, E.J. 1992. Comparative evaluation of Pacific Giant Salamander and steelhead trout populations among streams in old-growth and second-growth forests of Northwestern California. Ph.D. Dissertation, University of California, Davis.

Crouse, M. R., Callahan, C. A., Malueg, K. W. and Dominguez, S. E. 1981. Effects of fine sediments on growth of juvenile coho salmon in laboratory streams. Transaction of the American Fisheries Society 110:281-286.

Cummins, K. and M. A. Madej. 2004. Update on evaluating the composition of suspended load as a measure of stream health. January 2004 Monitoring Study Group Meeting Minutes. California Board of Forestry and Fire Protection. http://www.fire.ca.gov/CDFBOFDB/pdfs/MSG_January_2004.pdf

Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. W.H. Freeman and Company, New York. 818 p.

Environmental Science Associates. 2003. San Vicente pond and creek smolt outmigrant study, spring 2003. Summary Report. Prepared for NMFS on behalf of Coast Dairies & Land Company. 28 p + appendices

Frissell, C. 2005. Technical comments on the Proposed Washington State Forest Practices Habitat Conservation Plan. May 12, 2005. 16 p.

Hallock, R.J., Van Woert, W.F., and L. Shapovalov. 1961. An evaluation of stocking hatchery-reared steelhead rainbow trout (Salmo gairdnerii) in the Sacramento River system. CDFG Fish. Bull. No. 114.

Harvey, B.C. and S.F. Railsback. No date. Elevated turbidity reduces abundance and biomass of stream trout in an individual-based model.

Henley, W.F., Patterson, M.A., Neves, R.J. and A. D. Lemly. 2000. Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. Reviews in Fish. Sci. 8(2): 125-139.

Kabel, C.S. and E.R. German. 1967. Some aspects of stocking hatchery-reared steelhead and silver salmon. Marine Resources Branch Administrative Report No. 67-3. California Department of Fish and Game.

Knopp, C. 1993. Testing Indices of Cold Water Fish Habitat. Final Report for Development of Techniques for Measuring Beneficial Use Protection and Inclusion into the North Coast Region's Basin Plan by Amendment of the.....Activities, September 18, 1990. North Coast Regional Water Quality Control Board in cooperation with California Department of Forestry. 57 p.

Ligon, F., Rich, A., Rynearson, G., Thornburgh, and W. Trush. 1999. Report of the Scientific Review Panel on California Forest Practice Rules and Salmonid Habitat. Prepared for: The Resources Agency of California and the National Marine Fisheries Service, June 1999. 92 p. with appendices.

Lloyd, D. S. 1985. Turbidity in freshwater habitats of Alaska: a review of published and unpublished literature relevant to the use of turbidity as a water quality standard. Alaska Department of Fish and Game. Habitat Division. Report 85. Part 1.

Mast, M.A. and D.W. Clow. 2000. Environmental characteristics and water quality of Hydrologic Benchmark Network stations in the Western United States. USGS Circular No. 1173-D, 115 p.

McElhany, P., Ruckelshaus, M.H., Ford, M.J., Wainwright, T.C., and E.P. Bjorkstedt. 2000. Viable salmonid populations and the recovery of evolutionary units. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-NWFSC-42, 156 p.

McElhany, P., Busack, C., Chilcote, M., Kolmes, S., McIntosh, B., Myers, J., Rawding, D., Steel, A., Steward, C., Ward, D., Whitesel, T., and C. Willis. 2006. Revised viability criteria for salmon and steelhead in the Willamette and Lower Columbia basins. Review Draft, Willamette/Lower Columbia Technical Recovery Team, Oregon Department of Fish and Wildlife. April 1, 2006. 177 p.

Newcombe, C.P. and D.D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. No. Am. J. Fish. Management 11:72-82.

Newcombe, C.P. and J.O.T. Jensen. 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. No. Am. J. Fish. Management 16:693-727.

ODEQ. 2004. Draft Technical Basis for Revising Turbidity Criteria. Water Quality Division, Oregon Department of Environmental Quality. February 12, 2004 by Rosetta, T.

Peterson, N.P., Hendry, A., and T.P. Quinn. 1992. Assessment of cumulative effects on salmonid habitat: some suggested parameters and target conditions. Center for Streamside Studies, University of Washington, Seattle, WA, TFW-F3-92-001, March 2, 1992.

Reid, L.M. no date. Review of the Final EIS/EIR and HCP/SYP for the Headwaters Forest Project. USDA Forest Service Pacific Southwest Research Station, Redwood Sciences Laboratory, Arcata, CA. 80 p.

Regetz, J. 2002. Landscape-level constraints on recruitment of chinook salmon (Oncorhynchus tschawytscha) in the Columbia River basin, USA. Aquatic Conservation: Marine and Freshwater Ecosystems 13(1):35-49.

Ricker, S.J. 2003. 2002-2003 Annual Report: Results of juvenile salmonid downstream migrant trapping conducted on Freshwater Creek, 2003. Project 2a6. Steelhead Research and Monitoring Program. State of California, The Resources Agency, Department of Fish and Game. 15 p.

Rosenfeld, J. 2002. Modelling the effects of changes in turbidity and channel structure on growth of juvenile salmonids. Final 2002-2003 Project Report, Forestry Innovation Investment Research Program, FII R2003-183, B.C. Ministry of Water Land and Air Protection. 18 p.

Rowe, D. K., Dean, T. L., Williams, E. and Smith, J. P. (2003). Effects of turbidity on the ability of juvenile rainbow trout, Oncorhynchus mykiss, to feed on limnetic and benthic prey in laboratory tanks. New Zealand Journal of Marine and Freshwater Research 37(1):45-52.

Servizi, J.A. and D.W. Martens. 1992. Sublethal responses of coho salmon (Oncorhynchus kisutch) to suspended sediments. Canadian Journal of Fisheries and Aquatic Sciences 49:1389-1395.

Shapovalov, L. and A.C. Taft. 1954. The life histories of the steelhead rainbow trout (Salmo gairdneri gairdneri) and silver salmon (Oncorhynchus kisutch) with special reference to Waddell Creek, California, and recommendations regarding their management. California Department of Fish and Game Fish Bulletin No. 98. 375 p.

Sigler, J.W., Bjornn, T.C., and F.H. Everest. 1984. Effects of chronic turbidity on density and growth of steelheads and coho salmon. Transaction of the American Fisheries Society 113:142-150.

Sparkman, M. 2001. Redwood Creek Rotary Screw Trap Downstream Migration Study, Redwood Valley, Humboldt County, California, April 4 – August 5, 2000. Written for Doug Parkinson and prepared for Redwood Creek Landowners Association, January 16, 2001. 39 p.

Spence, B.C., Lomnicky, G.A., Hughes, R.M., and R.P. Novitzki. 1996. An ecosystem approach to salmonid conservation. Management Technology Report TR-4501-96-6057.
Sweka, J. A. and K.J. Hartman. 2001. Influence of turbidity on brook trout reactive distance and foraging success. Transactions of the American Fisheries Society 130:138-146.

Suttle, K.B., Power, M.E., Levine, J.M., and C. McNeely. 2004. How fine sediment in riverbeds impairs growth and survival of juvenile salmonids. Ecological Applications 14(4) pp. 969-974.

Sweka, J. A. and Hartman, K. J. 2001. Effects of turbidity on prey consumption and growth in brook trout and implications for bioenergetics modeling. Canadian Journal of Fisheries and Aquatic Sciences 58(2):386-393.

Tippets, W.E. and P.B. Moyle. 1978. Epibenthic feeding by rainbow trout (Salmo gairdneri) in the McCloud River, California. J. Animal Ecol. 47:549-559.

Trush, W. J. 1991. The Influence of Channel Morphology on Spawning Steelhead Trout in South Fork Eel River Tributaries. Ph.D. Dissertation, Department of Forestry and Natural Resources, University of California, Berkeley, CA.

Trush, W.J. 2001. Testimony of William J. Trush before the State Water Resources Control Board. June 25 and 26, 2001. Exhibit G.

Vaughn, H. 2000. Sproul Creek downstream migrant trapping program. Report submitted to Barnum Timber Company. Eel River Salmon Restoration Project. August 26, 2000. 6 p + appendix

Walters, D.M., Freeman, M.C., Leigh, D.S., Freeman, B.J., Paul, M.J., and C.M. Pringle. 2001. Bed texture and turbidity as indicators of fish biotic integrity in the Etowah River System. Proceedings of the 2001 Georgia Water Resources Conference. Athens, GA.

Ward, B.R., Slaney, P.A., Facchin, A.R., and R.W. Land. 1989. Size biased survival in steelhead trout (Oncorhynchus mykiss): back calculated lengths from adults' scales compared to migrating smolts at the Keogh River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 46:1853-1858.

Ward, B.R. 2006. The Case for Wild Steelhead Recovery without Artificial Fish Culture Intervention. Fisheries Scientist. Ministry of Environment, University of British Columbia, Vancouver. March 2006.

APPENDIX A. TURBIDITY DATA QUALITY ISSUES AND RESOLUTION.

Data Issue Resolution Method	**Code**
interpolated between good data	A
reduced to match values after cleaning sensor	B
synthesized data from similar storm at same site	C
synthesized data from similar storm at nearby site	D
extrapolated over baseflow period	E
synthesized data from discharge relationship	F

WY2003 (Dec 1 through May 31) **Station Name (Code)**	**Issue Type**	**No. Days Affected**	**Resolution Method**
Freshwater Creek at Roelofs (FTR)	missing data	3	C
	instantaneous spikes	8	A
Godwood Creek (GOD)	extended fouling	32	B
	instantaneous spikes	4	A
	missing data	22	E
Little Jones Creek (LJC)	raw data not acquired	---	---
Little Lost Man Creek (LLM)	instantaneous spikes	9	A
	extended fouling	5	B
Lost Man Creek at Hatchery (LMC)	missing data	12	E
	instantaneous spikes	13	A
Lower Jacoby Creek ab S. Quarry Road (JTG)	missing data	28	E
	extended fouling	4	A
	instantaneous spikes	13	A
North Fork Caspar Creek (NFC)	extended fouling	25	B
	instantaneous spikes	9	A
North Fork Elk River (KRW)	missing data	13	E
	extended fouling	27	A, B
South Fork Caspar Creek (SFC)	extended fouling	12	A, B
	instantaneous spikes	5	A
South Fork Lost Man Creek (SFL)	missing data	12	E
	instantaneous spikes	3	A
Upper Jacoby Creek (UJC)	missing data	1	E
	extended fouling	60	A, B
Upper Prairie Creek (PRU)	instantaneous spikes	2	A
	extended fouling	36	A, B

APPENDIX A. TURBIDITY DATA QUALITY ISSUES AND RESOLUTION (CONT.)

WY2004 (Dec 1 through May 31) Station Name	Issue Type	No. Days Affected	Resolution Method
Canoe Creek (CAN)	missing data	15	D
	extended fouling	55	A, B
	instantaneous spikes	14	A, B
Corrigan Creek (ESC)	raw data not acquired	---	---
Freshwater Creek at Roelofs (FTR)	instantaneous spikes	14	A, B
Godwood Creek (GOD)	extended fouling	19	A, B
	instantaneous spikes	5	A
Larry Damm Creek (LDC)	extended fouling	19	A, B
	instantaneous spikes	5	A
	missing data	15	D, E
Little Jones Creek (LJC)	raw data not acquired	---	---
Little Lost Man Creek (LLM)	extended fouling	14	A, B
	instantaneous spikes	1	A
Little South Fork Elk River (ESL)	raw data not acquired	---	---
Lost Man Creek at Hatchery (LMC)	extended fouling	1	A
	instantaneous spikes	6	A
	missing data	47	C, D
Lower Jacoby Creek at Brookwood (JBW)	extended fouling	38	A, B
	instantaneous spikes	7	A
Middle Fork Lost Man Creek (MFL)	extended fouling	44	A
	instantaneous spikes	6	A
Mill Creek (Garcia R trib) (MIL)	extended fouling	6	A
	instantaneous spikes	26	A
North Fork Caspar Creek (NFC)	extended fouling	33	A, B
	instantaneous spikes	2	A
North Fork Elk River (KRW)	extended fouling	83	A, B
	instantaneous spikes	1	A
North Fork Lost Man Creek (NFL)	missing data	3	A
	instantaneous spikes	1	A
Prairie Cr above Boyes Cr (PAB)	missing data	8	E
	extended fouling	45	A, B
	instantaneous spikes	10	A
Prairie Cr above May Cr (PRW)	extended fouling	45	A, B
	instantaneous spikes	14	A
S Branch NF Elk River (ENS)	raw data not acquired	---	---
South Fork Caspar Creek (SFC)	instantaneous spikes	4	A
South Fork Elk at M. Bohannon's (SFM)	extended fouling	41	A, B
	instantaneous spikes	15	A
South Fork Lost Man Creek (SFL)	extended fouling	14	A, B
	instantaneous spikes	6	A
SF Wages Creek ab Center Gulch (SFWAC)	missing data	13	F
	extended fouling	2	A, B
	instantaneous spikes	9	A
Upper Jacoby Creek (UJC)	extended fouling	8	A, B
	instantaneous spikes	4	A
Upper Prairie Creek (PRU)	extended fouling	2	A, B
	instantaneous spikes	2	A
Whitlow Creek (Garcia R Trib) (WHI)	extended fouling	2	A

APPENDIX A. TURBIDITY DATA QUALITY ISSUES AND RESOLUTION (CONT.)

WY2005 (Dec 1 through May 31)	Issue Type	No. Days Affected	Resolution Method
Station Name			
Canoe Creek (CAN)	missing data	12	A
	extended fouling	8	B
	instantaneous spikes	4	A
Corrigan Creek (ESC)	raw data not acquired	---	---
Freshwater Cr at HH Bridge (HHB)	raw data not acquired	---	---
Freshwater Creek at Roelofs (FTR)	instantaneous spikes	18	A
Godwood Creek (GOD)	extended fouling	24	A, B
	instantaneous spikes	9	A
Inman Creek (Garcia R Trib) (INM)	instantaneous spikes	3	A
	extended fouling	15	A
Larry Damm Creek (LDC)	none	---	---
Little Jones Creek (LJC)	extended fouling	9	A, B
	instantaneous spikes	14	A
Little Lost Man Creek (LLM)	extended fouling	35	A, B
	instantaneous spikes	1	A
Little South Fork Elk River (ESL)	raw data not acquired	---	---
Lost Man Creek at Hatchery (LMC)	extended fouling	25	A, B
	instantaneous spikes	8	A
Lower Jacoby Creek at Brookwood (JBW)	extended fouling	9	A, B
	instantaneous spikes	15	A
Middle Fork Lost Man Creek (MFL)	instantaneous spikes	1	A
	missing data	16	D
Mill Creek (Garcia R Trib) (MIL)	extended fouling	25	A, B
	instantaneous spikes	4	A
North Fork Caspar Creek (NFC)	extended fouling	9	A, B
	instantaneous spikes	4	A
North Fork Elk River (KRW)	extended fouling	24	A, B
	instantaneous spikes	3	A
North Fork Lost Man Creek (NFL)	instantaneous spikes	5	A
Prairie Cr above Boyes Cr (PAB)	extended fouling	13	A, B
	instantaneous spikes	4	A
Prairie Cr above May Cr (PRW)	extended fouling	64	A, B
	instantaneous spikes	13	A
S Branch NF Elk River (ENS)	raw data not acquired	---	---
SF Wages Creek AB Center Gulch (SFWAC)	extended fouling	24	A, B
South Fork Caspar Creek (SFC)	extended fouling	7	A, B
	instantaneous spikes	1	A
South Fork Elk at M. Bohannon's (SFM)	missing data	2	A
	extended fouling	1	A
South Fork Garcia R (SFK)	instantaneous spikes	1	A
South Fork Lost Man Creek (SFL)	extended fouling	41	A, B
	instantaneous spikes	4	A
Upper Jacoby Creek (UJC)	extended fouling	22	A, B
	instantaneous spikes	7	A
Upper Prairie Creek (PRU)	extended fouling	48	A, B
	instantaneous spikes	4	A
Whitlow Creek (Garcia R Trib) (WHI)	extended fouling	2	A, B
	instantaneous spikes	4	A

APPENDIX B. GIS DATA PROCESSING.

The sub-basins included in this study include public lands managed by different agencies with different levels of GIS mapping of base data. Some of the study basins have been mapped fairly intensively while others have not, resulting in varied-scale GIS base mapping data sources. We made efforts to avoid skewing any analysis based upon data mapping differences by using data for analysis purposes that was mapped at approximately the same scale across all basins. This required that we initially look at all of the data sources up-front and work with essentially the lowest common denominator of all of them. Much of this analysis relied heavily upon CDF timber-harvest-plan-associated data layers as this agency has been collecting data fairly consistently across these sub-basins with USGS DLG and digitized base data of roads and hydrography initially captured at 1:24,000 augmented with features digitized at 1:12,000 or better. The boundaries and feature representations of Timber Harvesting Plan (THP) boundaries are derived from the legal plan of record and include silvicultural units, yarding methods, ownership, and completion status. Metadata and contact information associated with these data is appended to this document. Roads, streams and THP boundaries were downloaded from CDF in May, 2006. Additionally, 10m USGS Digital Elevation Models (DEM) provided the basis of grid-related analyses, including slope, slope position, and Sinmap analyses.

Roads and Hydrography Data: Roads GIS data were based upon CDF THP-associated roads and streams layers. In instances when the roads data within multiple CDF-organized THP folders both covered the same sub-basin of interest but differed in terms of detail, the most extensive roads coverage for each study areas was chosen, which was consistent with the remaining basins.

Upper, Middle and Lower slope positions were defined by first classifying an entire grid from 0 to 100 where 0 represents valley floor and 100 represents ridge top. This grid was reclassified into polygons as follows: Lower slope position: 0-35; Middle Slope Position: 35-76; Upper Slope Position: 76-100. Roads were overlaid with slope position polygons.

Timber Harvest History: The timber harvest plan (THP) data used represent harvest plan approval by CDF; implementation may be slightly different than the approved plan if amendments are approved later, and there may be a time lag of up to three years, and in some rare cases five years, between approval and implementation. Because we only used THP data through 2004, the amount of yet-to-be-implemented plan area likely represents a small proportion of the total THP area used in the analysis.

SINMAP:

The SINMAP approach to modeling the spatial distribution of shallow debris slides combines a mechanistic infinite slope stability model with steady-state hydrology model (Pack and others, 1998a). The spatial distribution of this “stability index” is primarily determined by both slope and specific catchment area (upslope area per unit contour length), which were derived from 10m USGS Digital Elevation Models (DEMs). SINMAP allows adjustment or calibration of certain parameters pertaining to soil, vegetation, or geologic data, with the intent of producing an output stability map that “maximizes the proportion of observed landslides in regions with a low stability index, while minimizing the extent of low stability regions and consequent alienation of terrain to regions where landslides have not been observed." (Pack and others, 1998b). The accuracy of the output relies heavily on the accuracy of the DEM.

The model output is the "Stability Index". "The stability index produced is defined as the probability that a location is stable assuming uniform distributions of the parameters over input uncertainty ranges. The index value ranges between 0 (most unstable) and 1 (least unstable). Where the most conservative (destabilizing) set of parameters in the model still results in stability, the stability index is defined as the factor of safety (ratio of stabilizing to destabilizing forces) at this location under the most conservative set of parameters. This yields a value greater than 1." (Pack and others, 1998b, pg 4)

In this set of statistics, parameters were left uncertain while following uniform probability distributions between specified lower and upper bounds set to default values by the extension. Because uniform GIS landslide data across the various study watersheds does not exist, we did not calibrate parameters. The purpose of this exercise was to compare multiple watersheds using available GIS data without introducing any bias towards any particular watershed in the output stability map due to lack of or inconsistent GIS input data. For this reason, and combined with the fact that the primary driver of the spatial distribution of the stability index is determined by slope and specific catchment area, SINMAP output was produced using equivalent parameters on all study watersheds with 10m USGS DEMs as input. The output stability map or associated statistics are not intended as numerically precise, but are most appropriately interpreted in terms of relative hazard. (Pack and others, 1998b) For statistical purposes, the output stability index ranges were reclassified as follows: <1; 1-1.1; 1.1-1.2; >1.2. In terms of this model, it would be beneficial to obtain accurate and consistent (across the study watersheds) landslide inventory data and also parameter data for future evaluation of model outputs.

References:

Pack, R.T., Tarbaton, D.G., and Goodwin, C.N. 1998a. The SinMap approach to terrain stability mapping", Paper submitted to the 8th Congress of the International Association of Engineering Geology, Vancouver, British Columbia, Canada, 21-25 September, 1998.

Pack, R.T., Tarbaton, D.G., and Goodwin, C.N. 1998b. SinMap users manual: SINMAP: a stability index approach to terrain stability hazard mapping" Report Number 4114-0, Terratech Consulting Ltd., Salmon Arm, B.C., Canada.

Metadata:

1.0 Identification Information

1.1 Citation Information

1.11 Originator::California Department of Forestry and Fire Protection, Forest Practice GIS

1.12 Ten Year Timber Harvesting History

1.13 Type of Data::GIS Coverage Arc/Info v.8.3

1.2 Citation Details

Serial Information

1.21 NA

1.22 Issue Identification::NA

Publication Information

Publication Place::Santa Rosa, CA

1.22.1 Publisher:: California Department of Forestry and Fire Protection, Northern Region Forest Practice GIS

1.23 Publication Date:: 04/01/04

1.24 Other Citation Details:: updated quarterly

1.25 Data Set Description and Status

Description::

1.31 Abstract:: USGS DLG and digitized base data captured at 1:24,000 augmented with features digitized at 1:12,000 or better; boundaries and feature representations of Timber Harvesting Plans (THPs) are derived from the legal plan of record. Data is aggragated by Calwater 2.2 delimited hydrologic divisions.

1.311:: Coverages include hydrography, roads, timber harvest boundaries (silvicultural units, yarding methods, ownership, completion status)

1.32 Purpose:: Contribute to an assessment of cumulative effects from timber harvesting at the watershed level.

1.33 Supplemental Information:: Data is derived from maps contained in Timber Harvesting Plans (THPs), reflects that record, and is generally limited to what is required in the California Forest Practice Rules for the particular year the THP was approved.

1.34 Coordinate System Description::

Projection	UTM		
Zone	10		
Units	Meter	Spheroid	CLARKE1866
xshift	0.00000	yshift	-4000000.00
NAD 1927			

1.35 Time Period of Content:: 1994 – present

1.36 Progress:: in progress

1.37 Maintenance and Update Frequency:: As needed

1.4 Geographic Content:: Please indicate one or more of the following options.

1.41 Quads:: USGS 7.5 minute

1.42 Lat/long::

1.43 Calwater:: v 2.2

Klamath Glen Hydrologic Sub-Area
Scott River Hydrologic Area
Shasta Valley Hydrologic Area
Redwood Creek Hydrologic Unit
Trinidad Hydrologic Unit
Mad River Hydrologic Unit
Eureka Plain Hydrologic Unit
Eel River Hydrologic Unit
Cape Mendocino Hydrologic Unit
Mendocino Coast Hydrologic Unit

Russian River Hydrologic Unit

1.44 County::Del Norte, Humboldt, Mendocino, Sonoma

1.5 Keywords:: Forestry, Timber Harvesting Plans (THPs), Monitoring, Calwater, Watersheds

1.6 Constraints

1.61 Access Constraints Data is public record and available on CD-ROM or at ftp://ftp.fire.ca.gov/forest via anonymous login.

1.62 Use Constraints::Not for third party distribution.

2.0 Data Quality Information:: Data represented is a reflection of the public record and only is as accurate as the information contained within that record. Most data has not been ground truthed by CDF. Thoroughness of feature representation is limited to what is represented in the source material (Timber Harvesting Plans). RMS error ≤ .003

2.1 Scale:: digitized at 1:12,000 or greater

3.0 Data Location

3.1 Storage Location:: CA Dept. of Forestry and Fire Protection, Northern Region

Headquarters, Forest Practice GIS 135 Ridgway Ave. Santa Rosa, CA 95401

3.2 OnLine Linkage URL:: ftp://ftp.fire.ca.gov/forest

4.0 Metadata Reference Information

4.1 Metadata date:: 06/01/00
4.2 Metadata Contact:: Suzanne Lang
4.3 Metadata Contacts Organization:: CA Dept. of Forestry and Fire Protection
4.4 Metadata Contacts Address::135 Ridway Ave.
City::Santa Rosa
State::CA
Zip Code::95401
4.5 Metadata Contacts Voice Telephone::707-576-2955
4.6 Metadata Contacts Fax::707-576-2979
4.7 Metadata Contacts Email::suzanne.lang@fire.ca.gov
4.8 Metadata Standard Name:: FGDC Standards for Digital Geospatial Metadata
4.9 Metadata Standard Revision::June 1994 FGDC Standards

5.0 Data Contact Information

5.1 Contact Person Primary:: Suzanne Lang
5.2 Contact Organization:: CA Dept. of Forestry and Fire Protection
5.3 Contact Address:: 135 Ridway Ave.
City:: Santa Rosa
State::CA
Zip Code:95401
5.4 Contact Voice Telephone::707-576-2955
5.5 Contact Fax::707-576-2979
5.6 Contact email:: suzanne_lang@fire.ca.gov

APPENDIX C: WATERSHED VARIABLES

Variable Description (units) [code] > **Watershed**	**Gage Code (alpha-betical order)**	**WY2005 1% Exceed. Turbidity (FNU, FBU) [1%TU]**	**WY2005 10% Exceed. Turbidity (FNU, FBU) [10%TU]**	**Drainage Area (mi^2) [DRA]**	**Ave. Water-shed Slope (%) [AWS]**	**Perrenial Stream Density (mi/mi^2) [PSD]**	**Inter-mittent Stream Density (mi/mi^2) [ISD]**	**Total Stream Density (mi/mi^2) [TSD]**	**SINMAP Area FS<1 (%) [SIN<1]**	**SINMAP Area FS 1-1.1 (%) [SIN1.0]**	**SINMAP Area FS 1.1-1.2 (%) [SIN1.1]**
Canoe Creek [1]	CAN	225	56	10.11	43.04	0.91	1.44	2.35	37.9%	7.6%	8.5%
S Branch NF Elk River	ENS	483	76	1.89	30.62	0.71	1.42	2.13	16.4%	4.8%	7.5%
Corrigan Creek	ESC	249	50	1.58	33.15	0.00	1.78	1.78	19.4%	6.6%	8.2%
Little South Fork Elk River	ESL	31	12	1.18	22.67	0.26	1.10	1.36	8.7%	2.7%	3.3%
Freshwater Creek at Roelofs	FTR	254	57	12.77	38.20	1.13	0.98	2.12	19.1%	5.6%	6.9%
Godwood Creek [2]	GOD	23	6	1.48	29.14	1.11	0.57	1.68	15.2%	6.4%	7.4%
Freshwater Cr at HH Bridge	HHB	281	67	28.12	32.11	1.16	0.86	2.02	17.4%	5.2%	6.7%
Inman Creek (Garcia R Trib)	INM	127	26	7.53	43.35	1.03	0.59	1.62	39.9%	7.1%	7.0%
Lower Jacoby Creek	JBW	307	53	13.56	32.40	1.26	0.58	1.84	20.2%	4.1%	6.7%
North Fork Elk River	KRW	376	93	22.17	34.85	1.07	1.14	2.21	22.2%	6.8%	7.4%
Larry Damm Creek	LDC	106	16	1.84	26.32	1.28	0.57	1.85	11.8%	4.2%	5.0%
Little Jones Creek [1]	LJC	25	5	8.60	51.28	1.68	0.62	2.31	57.4%	6.5%	6.7%
Little Lost Man Creek [2]	LLM	77	16	3.52	29.34	1.54	0.00	1.54	17.6%	5.8%	9.1%
Lost Man Creek at Hatchery	LMC	131	18	12.08	30.27	1.36	0.66	2.02	23.4%	5.3%	7.2%
Middle Fork Lost Man Creek	MFL	157	21	2.26	35.88	1.41	1.08	2.49	25.4%	5.7%	7.4%
Mill Creek (Garcia R Trib)	MIL	99	18	3.63	39.41	0.99	1.97	2.96	32.7%	7.0%	5.6%
North Fork Caspar Creek [2]	NFC	107	33	1.87	36.32	1.07	0.84	1.90	24.8%	6.9%	8.1%
North Fork Lost Man Creek	NFL	145	18	2.22	33.76	1.29	0.80	2.09	21.6%	5.2%	6.3%
Prairie Cr above Boyes Cr	PAB	24	3	7.68	31.04	1.42	0.69	2.11	13.2%	4.8%	6.9%
Upper Prairie Creek [2]	PRU	26	6	4.16	29.17	1.59	0.62	2.21	9.9%	4.1%	6.5%
Prairie Cr above May Cr [2]	PRW	94	14	12.88	28.69	1.44	0.64	2.08	13.2%	4.8%	6.6%
South Fork Caspar Creek [2]	SFC	110	37	1.58	33.48	1.29	1.19	2.48	22.5%	6.4%	7.8%
South Fork Garcia R	SFK	71	11	1.33	44.59	0.74	1.67	2.41	45.4%	5.9%	6.0%
South Fork Lost Man Creek	SFL	197	22	3.94	38.56	1.29	0.58	1.87	30.8%	5.7%	8.8%
South Fork Elk at M. Bohannon's	SFM	551	116	19.30	29.62	0.80	0.99	1.79	10.6%	3.5%	4.9%
SF Wages ab Center Gulch	SFW	15	4	1.11	58.29	0.24	1.96	2.21	70.1%	6.8%	5.1%
Upper Jacoby Creek [2]	UJC	293	42	5.83	38.27	1.42	0.91	2.34	31.8%	5.0%	6.6%
Whitlow Creek (Garcia R Trib)	WHI	149	29	1.90	41.23	0.18	1.84	2.02	33.9%	7.0%	7.3%
Minimum =	**---**	**15**	**3**	**1.11**	**22.67**	**0.00**	**0.00**	**1.36**	**8.7%**	**2.7%**	**3.3%**
Maximum =	**---**	**551**	**116**	**28.12**	**58.29**	**1.68**	**1.97**	**2.96**	**70.1%**	**7.6%**	**9.1%**
Mean =	**---**	**169**	**33**	**7.00**	**35.54**	**1.06**	**1.00**	**2.06**	**25.4%**	**5.6%**	**6.8%**

[1] OBS-3 turbidity sensor data not adjusted; [2] OBS-3 turbidity sensor data adjusted to equivalent DTS-12 values

Appendix C: Watershed Variables (cont.’)

Variable Description (units) [code] > Watershed	SINMAP Area FS >1.2 (%) [SIN1.2]	Hypso-metric Integral (n/a) [HYP]	Basin Relief (feet) [RLF]	WY2005 Annual Rainfall Recur. Int. (yrs) [ANP]	WY2005 1-day Rainfall Recur. Int. (yrs) [1DP]	WY2005 2-day Rainfall Recur. Int. (yrs) [2DP]	WY2005 3-day Rainfall Recur. Int. (yrs) [3DP]	Basin-wide road density (mi/mi^2) [GRD]	Basin-wide lower slope road density (mi/mi^2) [LSRD]	Basin-wide mid-slope road density (mi/mi^2) [MSRD]	Basin-wide upper slope road density (mi/mi^2) [USRD]
Canoe Creek [1]	46.0%	0.500	3183	2.30	0.56	1.23	0.93	0.7	0.2	0.3	0.2
S Branch NF Elk River	71.2%	0.583	1656	2.30	0.56	1.23	0.93	7.0	3.8	2.3	1.0
Corrigan Creek	65.8%	0.709	1289	2.30	0.56	1.23	0.93	7.3	3.5	1.6	2.3
Little South Fork Elk River	85.4%	0.832	817	2.30	0.56	1.23	0.93	1.2	0.9	0.4	0.0
Freshwater Creek at Roelofs	68.4%	0.455	2776	2.30	0.56	1.23	0.93	6.3	1.5	1.8	3.0
Godwood Creek [2]	71.0%	0.501	696	1.82	0.49	0.98	0.65	2.9	1.6	0.5	0.8
Freshwater Cr at HH Bridge	70.7%	0.342	2162	2.30	0.56	1.23	0.93	7.7	1.9	2.4	3.4
Inman Creek (Garcia R Trib)	46.0%	0.474	1896	3.01	0.42	0.86	1.38	6.7	2.7	1.6	2.4
Lower Jacoby Creek	69.1%	0.511	2135	2.30	0.56	1.23	0.93	8.1	2.4	2.6	3.1
North Fork Elk River	63.6%	0.364	2294	2.30	0.56	1.23	0.93	7.3	1.9	2.0	3.4
Larry Damm Creek	79.1%	0.320	1618	1.82	0.49	0.98	0.65	1.1	0.7	0.2	0.2
Little Jones Creek [1]	27.7%	0.536	3059	0.44	1.67	2.66	4.69	2.6	0.0	0.0	0.0
Little Lost Man Creek [2]	67.6%	0.580	2086	1.82	0.49	0.98	0.65	0.8	0.6	0.0	0.2
Lost Man Creek at Hatchery	64.1%	0.485	1395	1.82	0.49	0.98	0.65	2.3	1.5	0.2	0.6
Middle Fork Lost Man Creek	61.6%	0.703	1669	1.82	0.49	0.98	0.65	3.0	2.0	0.2	0.9
Mill Creek (Garcia R Trib)	54.8%	0.698	983	3.01	0.42	0.86	1.38	4.9	2.3	0.9	1.7
North Fork Caspar Creek [2]	60.1%	0.666	774	3.01	0.42	0.86	1.38	5.0	0.0	0.3	4.7
North Fork Lost Man Creek	66.9%	0.568	1556	1.82	0.49	0.98	0.65	1.8	1.3	0.2	0.4
Prairie Cr above Boyes Cr	75.1%	0.492	1434	1.82	0.49	0.98	0.65	4.1	2.4	0.5	1.2
Upper Prairie Creek [2]	79.5%	0.499	1335	1.82	0.49	0.98	0.65	3.9	2.3	0.4	1.2
Prairie Cr above May Cr [2]	75.4%	0.368	1798	1.82	0.49	0.98	0.65	4.1	2.4	0.6	1.1
South Fork Caspar Creek [2]	63.3%	0.516	955	3.01	0.42	0.86	1.38	2.8	1.4	0.1	1.2
South Fork Garcia R	42.7%	0.435	1906	3.01	0.42	0.86	1.38	8.3	2.7	2.8	2.8
South Fork Lost Man Creek	54.8%	0.668	2004	1.82	0.49	0.98	0.65	3.3	2.1	0.3	1.0
South Fork Elk at M. Bohannon's	56.8%	0.417	1967	2.30	0.56	1.23	0.93	6.0	1.7	1.5	2.8
SF Wages ab Center Gulch	18.0%	0.649	1621	3.01	0.42	0.86	1.38	6.2	2.6	1.5	2.2
Upper Jacoby Creek [2]	56.7%	0.663	1641	2.30	0.56	1.23	0.93	7.1	1.7	2.1	3.2
Whitlow Creek (Garcia R Trib)	51.8%	0.499	1408	3.01	0.42	0.86	1.38	7.1	3.1	1.8	2.3
Minimum =	**18.0%**	**0.320**	**696**	**0.44**	**0.42**	**0.86**	**0.65**	**0.7**	**0.0**	**0.0**	**0.0**
Maximum =	**85.4%**	**0.832**	**3183**	**3.01**	**1.67**	**2.66**	**4.69**	**8.3**	**3.8**	**2.8**	**4.7**
Mean =	**61.2%**	**0.537**	**1718**	**2.24**	**0.54**	**1.10**	**1.08**	**4.6**	**1.8**	**1.0**	**1.7**

[1] OBS-3 turbidity sensor data not adjusted; [2] OBS-3 turbidity sensor data adjusted to equivalent DTS-12 values

APPENDIX C: WATERSHED VARIABLES (CONT.')

Variable Description (units) [code] > **Watershed**	**Clearcut Equiv. Area (%) 1990-2004 [CCE 0-15]**	**Clearcut Equiv. Area (%) 1995-2004 [CCE 0-10]**	**Clearcut Equiv. Area (%) 2000-2004 [CCE 0-5]**	**Clearcut Equiv. Area (%) 2000-2004 [CCE 5-10]**	**Clearcut Equiv. Area (%) 2000-2004 [CCE 10-15]**	**Tractor Yarded Area (%) [TYA-15]**	**Perma-nent (rocked) road density: THPs (mi/mi^2) [PRC-15]**	**Seasonal road cons-tructed (mi/mi^2) [SRC-15]**	**Temp. & 4WD roads cons-tructed (mi/mi^2) [TRC-15]**	**Temp & seas. roads cons-tructed (unsurfaced) (mi/mi^2) [TSR-15]**	**All non-paved roads cons-tructed (mi/mi^2) [ARC-15]**
Canoe Creek [1]	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	0.37	0.36	0.45	0.80	1.17
S Branch NF Elk River	1.63%	0.46%	0.50%	0.42%	3.98%	30.2%	4.60	3.95	0.36	4.31	8.91
Corrigan Creek	2.40%	2.27%	4.54%	0.01%	2.64%	43.5%	2.11	5.53	1.27	6.80	8.91
Little South Fork Elk River	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	1.28	0.00	0.00	0.00	1.28
Freshwater Creek at Roelofs	2.74%	3.56%	3.37%	3.76%	1.10%	29.6%	3.18	4.09	0.00	4.09	7.27
Godwood Creek [2]	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	0.00	5.93	0.00	5.93	5.9
Freshwater Cr at HH Bridge	3.61%	4.31%	4.25%	4.37%	2.20%	39.7%	3.24	5.16	0.11	5.27	8.51
Inman Creek (Garcia R Trib)	1.71%	1.10%	0.00%	2.20%	2.93%	35.7%	1.61	5.85	0.51	6.35	7.96
Lower Jacoby Creek	1.58%	1.71%	1.70%	1.71%	1.32%	27.8%	1.83	7.16	0.15	7.31	9.14
North Fork Elk River	3.65%	3.54%	3.58%	3.51%	3.87%	37.7%	3.43	4.44	0.10	4.54	7.97
Larry Damm Creek	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	0.76	0.29	1.2	1.47	2.2
Little Jones Creek [1]	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	0.68	2.66	0.2	2.81	3.5
Little Lost Man Creek [2]	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	2.06	2.05	0.0	2.05	4.1
Lost Man Creek at Hatchery	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	0.89	1.87	1.1	2.93	3.8
Middle Fork Lost Man Creek	0.01%	0.01%	0.02%	0.00%	0.00%	0.1%	0.84	2.00	2.4	4.37	5.2
Mill Creek (Garcia R Trib)	0.68%	0.93%	1.00%	0.86%	0.18%	12.4%	0.12	4.80	0.66	5.46	5.59
North Fork Caspar Creek [2]	0.74%	0.00%	0.00%	0.00%	2.21%	2.9%	2.20	4.57	0.15	4.71	6.92
North Fork Lost Man Creek	0.00%	0.00%	0.00%	0.01%	0.00%	0.0%	0.00	2.76	0.82	3.57	3.57
Prairie Cr above Boyes Cr	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	1.70	0.00	0.4	0.37	2.1
Upper Prairie Creek [2]	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	2.55	0.00	0.0	0.00	2.6
Prairie Cr above May Cr [2]	0.00%	0.00%	0.01%	0.00%	0.00%	0.0%	1.84	0.00	0.4	0.36	2.2
South Fork Caspar Creek [2]	0.05%	0.06%	0.00%	0.13%	0.03%	1.5%	0.92	4.45	0.00	4.45	5.37
South Fork Garcia R	1.02%	1.52%	2.47%	0.58%	0.01%	12.7%	1.80	7.86	1.08	8.94	10.74
South Fork Lost Man Creek	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	0.84	2.89	0.9	3.78	4.6
South Fork Elk at M. Bohannon's	1.61%	1.21%	1.53%	0.88%	2.43%	14.5%	0.80	3.77	0.56	4.34	5.14
SF Wages ab Center Gulch	0.85%	1.25%	0.00%	2.49%	0.07%	0.7%	2.28	6.82	0.75	7.57	9.86
Upper Jacoby Creek [2]	1.57%	1.78%	1.31%	2.25%	1.15%	32.8%	1.83	6.46	0.02	6.49	8.32
Whitlow Creek (Garcia R Trib)	2.99%	2.15%	0.00%	4.31%	4.66%	56.7%	1.60	5.58	1.63	7.21	8.81
Minimum =	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.0%**	**0.0**	**0.0**	**0.0**	**0.0**	**1.2**
Maximum =	**3.65%**	**4.31%**	**4.54%**	**4.37%**	**4.66%**	**56.7%**	**4.6**	**7.9**	**2.4**	**8.9**	**10.7**
Mean =	**0.96%**	**0.92%**	**0.87%**	**0.98%**	**1.03%**	**13.5%**	**1.6**	**3.6**	**0.5**	**4.2**	**5.8**

[1] OBS-3 turbidity sensor data not adjusted; [2] OBS-3 turbidity sensor data adjusted to equivalent DTS-12 values

APPENDIX D. GEOLOGY BY PERCENT AREA (DOMINANT IN BOLD).

Station Name	Code	(mi2)	acres	fg	fm	Jg	Jum	Jv	K	Kga	KJf	KJfl	KJfs	KJf-SS	Ku
Canoe Creek	CAN	10.11	6471	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S Branch NF Elk River	ENS	1.89	1211	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Corrigan Creek	ESC	1.58	1013	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Little South Fork Elk River	ESL	1.18	756	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Freshwater Creek at Roelofs	FTR	12.77	8175	0%	3%	0%	0%	0%	0%	0%	**38%**	0%	29%	0%	0%
Godwood Creek	GOD	1.56	750	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Freshwater Cr at HH Bridge	HHB	28.12	17994	0%	5%	0%	0%	0%	0%	0%	17%	0%	30%	0%	0%
Inman Creek (Garcia R Trib)	INM	7.53	4818	0%	0%	0%	0%	0%	0%	0%	**61%**	0%	0%	0%	0%
Lower Jacoby Creek	JBW	13.56	8681	0%	39%	0%	0%	0%	0%	0%	0%	0%	**42%**	0%	0%
North Fork Elk River	KRW	22.17	14188	0%	0%	0%	0%	0%	0%	0%	13%	0%	3%	0%	1%
Larry Damm Creek	LDC	1.84	1180	0%	0%	0%	0%	0%	0%	0%	0%	27%	0%	0%	0%
Little Jones Creek	LJC	8.60	5505	0%	0%	**83%**	11%	0%	0%	0%	0%	0%	0%	0%	0%
Little Lost Man Creek	LLM	3.52	2250	0%	0%	0%	0%	0%	0%	0%	0%	**97%**	0%	0%	0%
Lost Man Creek at Hatchery	LMC	12.08	7725	0%	0%	0%	0%	0%	0%	0%	0%	**67%**	0%	0%	0%
Middle Fork Lost Man Creek	MFL	2.26	1443	0%	0%	0%	0%	0%	0%	0%	0%	**60%**	0%	0%	0%
Mill Creek (Garcia R Trib)	MIL	3.63	2324	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
North Fork Caspar Creek	NFC	1.87	1196	0%	0%	0%	0%	0%	**83%**	0%	0%	0%	0%	0%	0%
North Fork Lost Man Creek	NFL	2.22	1420	0%	0%	0%	0%	0%	0%	0%	0%	48%	0%	0%	0%
Prairie Cr above Boyes Cr	PAB	7.68	4777	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	32%	0%
Upper Prairie Creek	PRU	4.16	2660	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	27%	0%
Prairie Cr above May Cr	PRW	12.88	7863	0%	0%	0%	0%	0%	0%	0%	0%	6%	0%	20%	0%
South Fork Caspar Creek	SFC	1.58	1009	0%	0%	0%	0%	0%	**79%**	0%	0%	0%	0%	0%	0%
South Fork Garcia R	SFK	1.33	853	4%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%
South Fork Lost Man Creek	SFL	3.94	2522	0%	0%	0%	0%	0%	0%	0%	0%	**93%**	0%	0%	0%
South Fork Elk at M. Bohannon's	SFM	19.32	12363	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
SF Wages ab Center Gulch	SFW	1.11	712	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Upper Jacoby Creek	UJC	5.83	3734	0%	43%	0%	0%	0%	0%	0%	1%	0%	**52%**	0%	0%
Whitlow Creek (Garcia R Trib)	WHI	1.90	1218	0%	0%	0%	0%	0%	0%	0%	**99%**	0%	0%	0%	0%

APPENDIX D. GEOLOGY BY PERCENT AREA (DOMINANT IN BOLD) (CONT'.).

Station Name	Q	Qal	Qc	Qf	Qh	Qls	Qmts-l	Qmts-u	Qods	Qrt	Qt	QTc	QTfa	QTwu
Canoe Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S Branch NF Elk River	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**85%**
Corrigan Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**77%**
Little South Fork Elk River	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**100%**
Freshwater Creek at Roelofs	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	23%
Godwood Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**100%**	0%	0%	0%
Freshwater Cr at HH Bridge	1%	0%	0%	0%	2%	0%	0%	0%	0%	2%	0%	0%	0%	**40%**
Inman Creek (Garcia R Trib)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Lower Jacoby Creek	0%	0%	0%	0%	4%	0%	0%	0%	0%	1%	0%	0%	13%	0%
North Fork Elk River	1%	0%	0%	0%	1%	0%	0%	0%	0%	2%	0%	0%	0%	**65%**
Larry Damm Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**72%**	0%	0%
Little Jones Creek	0%	0%	0%	0%	0%	5%	0%	0%	0%	0%	0%	0%	0%	0%
Little Lost Man Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%	0%	0%
Lost Man Creek at Hatchery	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	32%	0%	0%
Middle Fork Lost Man Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	40%	0%	0%
Mill Creek (Garcia R Trib)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
North Fork Caspar Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
North Fork Lost Man Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**52%**	0%	0%
Prairie Cr above Boyes Cr	0%	0%	11%	0%	0%	0%	0%	0%	0%	0%	**57%**	0%	0%	0%
Upper Prairie Creek	0%	0%	8%	0%	0%	0%	0%	0%	0%	0%	**65%**	0%	0%	0%
Prairie Cr above May Cr	0%	8%	7%	0%	0%	0%	0%	0%	0%	0%	**44%**	16%	0%	0%
South Fork Caspar Creek	0%	0%	0%	0%	0%	0%	0%	13%	2%	0%	0%	0%	0%	0%
South Fork Garcia R	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%
South Fork Lost Man Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	7%	0%	0%
South Fork Elk at M. Bohannon's	1%	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	**76%**
SF Wages ab Center Gulch	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Upper Jacoby Creek	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	4%	0%
Whitlow Creek (Garcia R Trib)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

APPENDIX D. GEOLOGY BY PERCENT AREA (DOMINANT IN BOLD) (CONT'.).

Station Name	TKf	TKfs	TKfs-g	TKy	Tm	Dom	Subdom	%Qtwu	CCE-15	10% TU
Canoe Creek	0%	0%	0%	**100%**	0%	**TKy**	<10%	0.0%	0.0%	56
S Branch NF Elk River	0%	0%	0%	15%	0%	**QTwu**	**TKy**	85.0%	24.5%	76
Corrigan Creek	0%	0%	0%	23%	0%	**QTwu**	**TKy**	76.6%	31.2%	50
Little South Fork Elk River	0%	0%	0%	0%	0%	**QTwu**	<10%	100.0%	0.0%	12
Freshwater Creek at Roelofs	0%	0%	0%	6%	0%	**KJf**	**KJfs**	23.1%	42.9%	57
Godwood Creek	0%	0%	0%	0%	0%	**Qt**	<10%	0.0%	0.0%	5
Freshwater Cr at HH Bridge	0%	0%	0%	3%	0%	**QTwu**	**KJf**	39.7%	53.6%	67
Inman Creek (Garcia R Trib)	39%	0%	0%	0%	0%	**KJf**	**Tkf**	0.0%	26.0%	26
Lower Jacoby Creek	0%	0%	0%	0%	0%	**KJfs**	**fm**	0.0%	23.8%	53
North Fork Elk River	0%	0%	0%	8%	6%	**QTwu**	**KJfs**	65.1%	51.9%	93
Larry Damm Creek	0%	0%	0%	0%	0%	**QTc**	**KJfl**	0.0%	0.0%	16
Little Jones Creek	0%	0%	0%	0%	0%	**Jg**	**Jum**	0.0%	0.0%	5
Little Lost Man Creek	0%	0%	0%	0%	0%	**KJfl**	<10%	0.0%	0.0%	15
Lost Man Creek at Hatchery	0%	0%	0%	0%	0%	**KJfl**	**QTc**	0.0%	0.0%	18
Middle Fork Lost Man Creek	0%	0%	0%	0%	0%	**KJfl**	**QTc**	0.0%	0.1%	21
Mill Creek (Garcia R Trib)	**100%**	0%	0%	0%	0%	**TKf**	<10%	0.0%	10.5%	18
North Fork Caspar Creek	0%	17%	0%	0%	0%	**K**	**TKfs**	0.0%	11.0%	29
North Fork Lost Man Creek	0%	0%	0%	0%	0%	**QTc**	**KJfl**	0.0%	0.0%	18
Prairie Cr above Boyes Cr	0%	0%	0%	0%	0%	**Qt**	**KJf-SS**	0.0%	0.0%	3
Upper Prairie Creek	0%	0%	0%	0%	0%	**Qt**	**KJf-SS**	0.0%	0.0%	5
Prairie Cr above May Cr	0%	0%	0%	0%	0%	**Qt**	**KJf-SS**	0.0%	0.0%	12
South Fork Caspar Creek	0%	5%	0%	0%	0%	**K**	**Qmts-l**	0.0%	0.8%	32
South Fork Garcia R	0%	**94%**	0%	0%	0%	**TKfs**	**fg**	0.0%	16.0%	11
South Fork Lost Man Creek	0%	0%	0%	0%	0%	**KJf**	<10%	0.0%	0.0%	22
South Fork Elk at M. Bohannon's	0%	0%	0%	20%	0%	**QTwu**	**TKy**	76.2%	25.3%	116
SF Wages ab Center Gulch	0%	**100%**	0%	0%	0%	**TKfs**	<10%	0.0%	12.8%	4
Upper Jacoby Creek	0%	0%	0%	0%	0%	**KJfs**	**fm**	0.0%	23.8%	34
Whitlow Creek (Garcia R Trib)	1%	0%	0%	0%	0%	**KJf**	<10%	0.0%	44.8%	29

APPENDIX E: CORRELATION MATRIX

Variable	*10% FNU*	*DRA*	*AWS*	*PSD*	*ISD*	*TSD*	*SIN<1*	*SIN 1.0*	*SIN 1.1*	*SIN>1.2*	*HYP*	*RLF*	*ANP*	*1DP*	*2DP*	*3DP*	*GRD*
10% FNU	1																
DRA	0.62	1.00															
AWS	-0.19	-0.13	1.00														
PSD	-0.19	0.23	-0.17	1.00													
ISD	0.13	-0.23	0.43	-0.76	1.00												
TSD	-0.06	-0.04	0.41	0.22	0.47	1.00											
SIN<1	-0.30	-0.21	0.97	-0.18	0.40	0.36	1.00										
SIN 1.0	-0.13	-0.17	0.64	-0.13	0.34	0.33	0.60	1.00									
SIN 1.1	0.06	-0.03	0.04	0.28	-0.26	0.00	-0.02	0.53	1.00								
SIN>1.2	0.12	0.11	-0.95	0.19	-0.39	-0.33	-0.96	-0.60	-0.01	1.00							
HYP	-0.27	-0.59	0.12	-0.32	0.29	0.00	0.18	0.06	-0.01	-0.12	1.00						
RLF	0.30	0.54	0.35	0.31	-0.25	0.05	0.27	0.00	0.12	-0.32	-0.42	1.00					
ANP	0.20	-0.14	0.21	-0.57	0.60	0.13	0.18	0.32	-0.10	-0.18	0.11	-0.41	1.00				
1DP	-0.04	0.16	0.29	0.27	-0.20	0.07	0.31	0.02	-0.03	-0.33	-0.02	0.56	-0.68	1.00			
2DP	0.12	0.27	0.21	0.20	-0.17	0.02	0.22	-0.08	-0.06	-0.24	-0.01	0.59	-0.66	0.98	1.00		
3DP	-0.14	-0.01	0.60	0.07	0.11	0.25	0.62	0.35	-0.05	-0.63	0.05	0.40	-0.26	0.85	0.78	1.00	
GRD	0.51	0.34	0.37	-0.41	0.50	0.20	0.26	0.25	0.07	-0.29	-0.18	0.23	0.53	-0.15	-0.05	0.02	1.00
LSRD	0.25	0.03	0.18	-0.46	0.54	0.19	0.12	0.10	0.06	-0.15	-0.05	0.02	0.31	-0.23	-0.18	-0.16	0.66
MSRD	0.56	0.41	0.31	-0.38	0.42	0.11	0.24	0.05	-0.11	-0.27	-0.26	0.41	0.37	0.03	0.16	0.12	0.91
USRD	0.40	0.35	0.35	-0.18	0.28	0.17	0.23	0.38	0.18	-0.25	-0.12	0.14	0.54	-0.15	-0.08	0.06	0.80
CCE 0-15	0.71	0.56	0.16	-0.42	0.37	0.00	0.03	0.24	0.10	-0.09	-0.29	0.34	0.40	-0.08	0.06	-0.02	0.80
CCE 0-10	0.60	0.62	0.20	-0.32	0.34	0.08	0.08	0.19	0.01	-0.10	-0.32	0.42	0.33	-0.06	0.08	-0.03	0.75
CCE 0-5	0.60	0.55	0.00	-0.28	0.30	0.06	-0.10	0.08	0.07	0.06	-0.23	0.35	0.18	0.00	0.15	-0.07	0.65
CCE 5-10	0.44	0.52	0.34	-0.27	0.30	0.08	0.23	0.25	-0.04	-0.23	-0.32	0.38	0.40	-0.10	-0.01	0.02	0.66
CCE 10-15	0.69	0.30	0.04	-0.47	0.32	-0.15	-0.05	0.25	0.21	-0.04	-0.16	0.11	0.39	-0.09	0.01	0.01	0.65
TYA	0.58	0.34	0.13	-0.45	0.39	-0.03	0.03	0.25	0.16	-0.06	-0.17	0.23	0.40	-0.09	0.04	-0.01	0.79
PRC-15	0.46	0.32	0.00	-0.18	0.14	-0.05	-0.09	-0.02	0.21	0.12	-0.18	0.30	0.21	-0.09	0.03	-0.12	0.57
SRC-15	0.29	0.03	0.54	-0.40	0.47	0.16	0.51	0.51	0.14	-0.54	0.03	0.06	0.58	-0.12	-0.08	0.16	0.73
TRC-15	-0.15	-0.29	0.18	-0.28	0.38	0.19	0.20	0.18	0.03	-0.21	0.13	-0.08	0.07	-0.19	-0.25	-0.12	0.00
TSR-15	0.24	-0.04	0.57	-0.45	0.54	0.20	0.55	0.54	0.14	-0.58	0.06	0.04	0.58	-0.16	-0.14	0.12	0.71
ARC-15	0.40	0.09	0.51	-0.48	0.54	0.16	0.45	0.47	0.21	-0.47	-0.02	0.16	0.60	-0.18	-0.11	0.06	0.86

APPENDIX E: CORRELATION MATRIX (CONT'.)

Variable	*LSRD*	*MSRD*	*USRD*	*CCE 0-15*	*CCE 0-10*	*CCE 0-5*	*CCE 5-10*	*CE 10-*	*TYA*	*PRC-15*	*SRC-15*	*TRC-15*	*TSR-15*	*ARC-15*
10% FNU														
DRA														
AWS														
PSD														
ISD														
TSD														
SIN<1														
SIN 1.0														
SIN 1.1														
SIN>1.2														
HYP														
RLF														
ANP														
1DP														
2DP														
3DP														
GRD														
LSRD	1.00													
MSRD	0.57	1.00												
USRD	0.12	0.63	1.00											
CCE 0-15	0.40	0.78	0.69	1.00										
CCE 0-10	0.30	0.76	0.68	0.94	1.00									
CCE 0-5	0.28	0.67	0.57	0.78	0.87	1.00								
CCE 5-10	0.24	0.66	0.62	0.86	0.87	0.51	1.00							
CCE 10-15	0.45	0.59	0.51	0.81	0.57	0.40	0.59	1.00						
TYA	0.53	0.76	0.59	0.92	0.80	0.64	0.76	0.85	1.00					
PRC-15	0.33	0.54	0.48	0.60	0.53	0.47	0.46	0.55	0.50	1.00				
SRC-15	0.35	0.70	0.65	0.54	0.53	0.43	0.50	0.40	0.56	0.14	1.00			
TRC-15	0.31	-0.08	-0.17	-0.04	-0.09	-0.08	-0.08	0.05	0.06	-0.29	0.01	1.00		
TSR-15	0.41	0.66	0.59	0.51	0.50	0.40	0.47	0.40	0.56	0.06	0.97	0.25	1.00	
ARC-15	0.50	0.81	0.72	0.70	0.66	0.54	0.60	0.58	0.70	0.46	0.92	0.10	0.92	1.00

APPENDIX F: WATERSHED MAPS

(provided under separate cover)