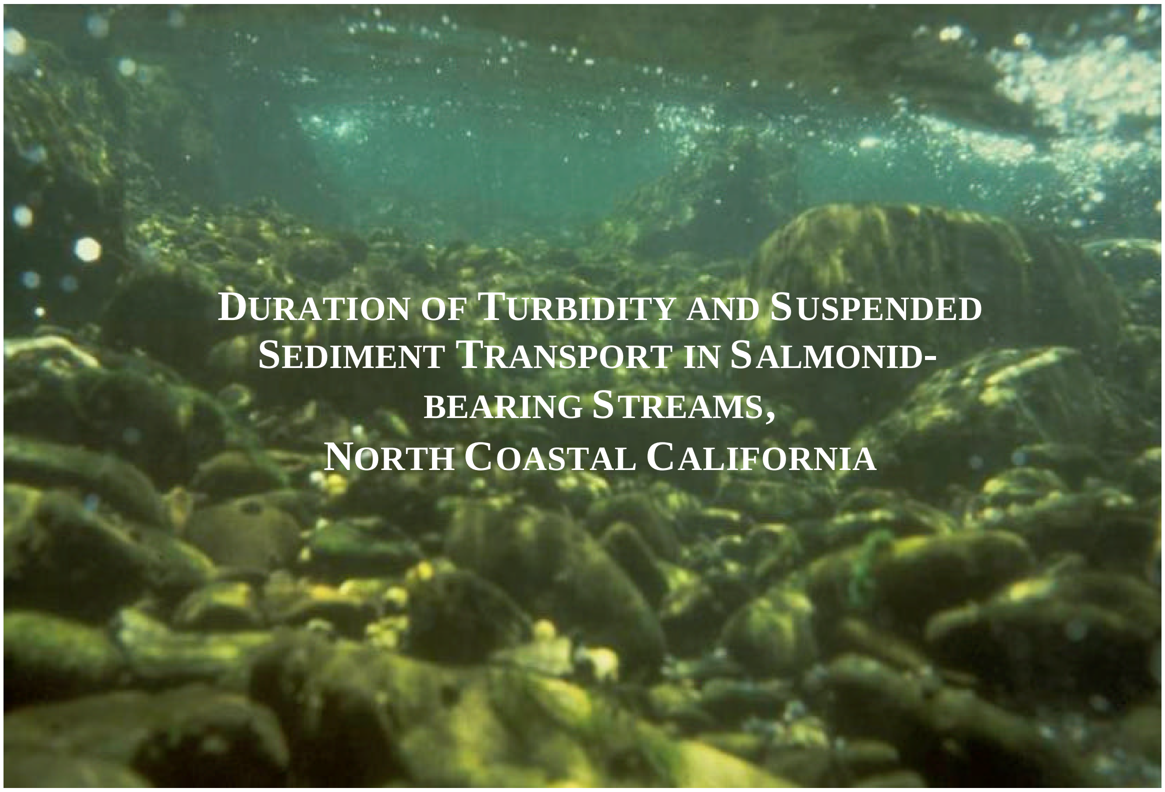

DURATION OF TURBIDITY AND SUSPENDED SEDIMENT TRANSPORT IN SALMONID-BEARING STREAMS, NORTH COASTAL CALIFORNIA

A Report to the US Environmental Protection Agency (USEPA)
Region IX
75 Hawthorne Street
San Francisco, California 94105

Prepared by:

Randy Klein, Hydrologist
Redwood National and State Parks

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ABSTRACT

Turbidity in northcoast streams and rivers is largely a function of the amount of sediment carried in suspension by flowing water. It is an integral part of the hydrological, geomorphical, and biological processes of streams and rivers in the northcoast of California and elsewhere. However, water quality and beneficial uses of water can suffer as a result of excessive turbidity, both in terms of increased magnitude and duration of turbidity over background levels. This study focused on “chronic turbidity’, or the tendency for some streams to remain turbid for a relatively large proportion of the winter runoff period.

The effects of chronic turbidity on aquatic biota are well-documented, and rural landowners and municipalities who depend on river water are keenly aware of problems arising from excessively and/or chronically turbid water. However, the causes of chronic turbidity are less well understood. Streams vary naturally in the magnitude and duration of turbidity for several reasons, including drainage size, soil and geologic makeup, tectonic setting, and slope steepness. However, human disturbance from agriculture, rangeland conversion, road building, timber harvest, and other land uses can elevate erosion and sediment yield and, consequently, turbidity magnitude and duration.

In this study, I assembled turbidity data from eight continuous turbidity and stage recording stations located on small streams in the northcoast region. Data from individual streams spanning three water years (WY2000-2002) were processed to calculate lengths of time turbidity was higher than several thresholds. Turbidity exceedence analyses, similar to conventional flow exceedence analyses, were also performed, allowing comparison of turbidity levels at various exceedence probabilities. The lowest (and most frequently appearing in the literature on salmonid impacts) threshold was 25 NTU, though inconsistencies in the threshold of impacts to salmonids exist in the literature. To complement the turbidity data, GIS analyses of land and land use characteristics for basin areas upstream of each gaging station were performed. Both natural and human-affected characteristics were summarized.

Differences between the study streams in duration of turbidity at several levels (the lowest being 25 NTU) spanned up to two orders of magnitude in some cases. A broad range of turbidities at the 1% and 10% exceedence probabilities was also observed between the study streams. These differences are considered to be far too great to be explained solely by natural variability (geology, climate), thus land use is concluded to be a dominant factor. Although limited by the number of sites assessed (eight), land use variables, particularly road density and annual rate of timber harvest, appeared to be the dominant controls on the gross differences in chronic turbidity observed among the study streams.

INTRODUCTION

Biological Effects of Turbidity

A large body of scientific literature exists on effects of turbidity and suspended sediment on aquatic biota (see review by Henley and others, 2000). Relatively low turbidities (above about 20-25 NTU, according to most studies) and suspended sediment concentrations (above about 25 mg/l) reduce ‘reactive distance’ (the distance at which food can be sighted under varying levels of water clarity) for juvenile salmonids. Even relatively low turbidities may impair the ability of juvenile salmonids to forage for food and attain sizes needed for ocean survival (Newcombe and MacDonald, 1991; Newcombe and Jensen, 1996; Sigler and others, 1984), although a few studies suggest higher thresholds (e.g., 150 NTU in Gregory and Northcote, 1993).

Large smolt outmigrant size has been shown to increase the chances of a fish returning as a spawning adult, so suppression of feeding and growth for a cohort can result in poor escapement numbers (returning spawners), even if smolt outmigration numbers are relatively high (Nicholas and Hankin, 1989). A host of other effects has been identified on salmonids, including behavioral effects (Berg and Northcote, 1984; Barrett and others, 1992) and mortality during egg incubation (Slaney and others, 1977). In addition to effects on juvenile fish feeding ability, turbid water diminishes the amount of sunlight reaching the streambed, which suppresses primary production (Henley and others, 2000).

A limitation in frequently cited studies is that in order to control the many variables that can influence fish survival and fitness, they were conducted in laboratory settings. But in streams, fish are subject to a host of compounding influences. For example, if both the feeding ability of fish and food availability (primary production) are reduced from chronic turbidity, impacts to fish can be additive or perhaps synergistic. Thus, the cumulative effects that may occur in streams is not well-characterized in laboratory settings where all but one variable (e.g., turbidity) is held constant. Although labor (and money) intensive, research conducted in natural stream environments is needed to better evaluate the effects of chronic turbidity.

Erosion, Sedimentation, and Chronic Turbidity

By adding very fine (suspendable) sediment to the stream channel system over background levels, land management has a tendency to both elevate turbidities and suspended sediment concentrations during winter storms and increase the duration of turbid flows between storms, a phenomenon referred to as “chronic turbidity”. Monitoring of suspended sediment and turbidity has traditionally focused on stormflows, relatively brief periods when they are very high. However, recent technological advances that allow automated recording of turbidity permit assessment of chronic turbidity. For this study, I assembled continuous turbidity records for eight streams draining northcoast watersheds and compared durations of a variety of turbidity levels.

Increased erosion and sedimentation from land management activities has 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.); things 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 in such large events. The yardstick by which we typically evaluate the magnitude of effects is the volumetric proportion of the sediment budget generated by a particular erosion process or resulting from a particular management practice.

To be sure, geomorphically large events are important determinants of the health of aquatic ecosystems that can have long-lasting effects, and a 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 represent relatively small volumes in a long-term sediment budget.

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 that were exceeded only 5% of the time (5% exceedence flow) transported about 80% of the total suspended sediment load. Conversely, sediment yield or transport occurring the rest of the time (the other 95%) represents only 20% of the total sediment load, but may represent an important component of chronic turbidity and thus have disproportionately large effects on aquatic biota due to the extended duration of exposure.

Suspended sediment transport at low concentrations can occur during small storms and between storms for some length of time after the peak has passed. Traveling around the northcoast of California, it is easy to notice that some streams tend to clear up much faster than others following cessation of rainfall. Differences between streams are especially apparent during recessional stormflows and winter baseflows; times when some streams have become virtually clear while others remain quite turbid. To protect and restore water quality and beneficial uses, it is important to determine the extent to which land management contributes to elevated fine sediment loads and the tendency for streams to experience extended periods of turbidity during the winter.

In California, the State’s Forest Practice Rules (FPRs) attempt to minimize logging-related erosion primarily through the use of restrictions on harvesting and yarding methods. The rules are, in effect, ‘best management practices’ (BMPs). Although much improved relative to earlier (pre-FPR) practices, current FPRs cannot prevent all erosion and stream sedimentation from logging. Perhaps the best example of this is a recent study done in Caspar Creek (Jackson State Forest, Mendocino County) undertaken by the US Forest Service, Redwood Sciences Laboratory (RSL) and funded by the California Department of Forestry and Fire Protection (CDF). The study was designed to compare erosion and sediment yield from a second-growth redwood forest (the South Fork of Caspar Creek) with that from adjacent areas logged under contemporary FPRs (North Fork Caspar Creek) using a variety of silvicultural and yarding methods and harvest levels.

From the Caspar Creek study, Rice (1996) found that erosion within logged sub-basins in the North Fork Caspar Creek (74 tonnes/ha) was, on average, over 10 times that occurring within the second-growth ‘control’ sub- basins (6.7 tonnes/ha), despite the use of relatively benign harvest practices (e.g., limiting tractor logging to gentle slopes, locating roads along ridgetops). He also found that erosion generally increased proportionally with the percent of the area logged and that sediment yield was much less than erosion over the course of the study period, owing to hillslope and channel storage of a large proportion of eroded materials. It is likely that sediment yield will account for an increasing proportion of erosion over time as temporarily stored material works its way downslope and downstream.

STUDY STREAMS

Figure 1 shows the eight streams for which turbidity data for this study were assembled. They span much of the geographical range of the northcoast and capture much of the climatic, topographical, and geological variability.

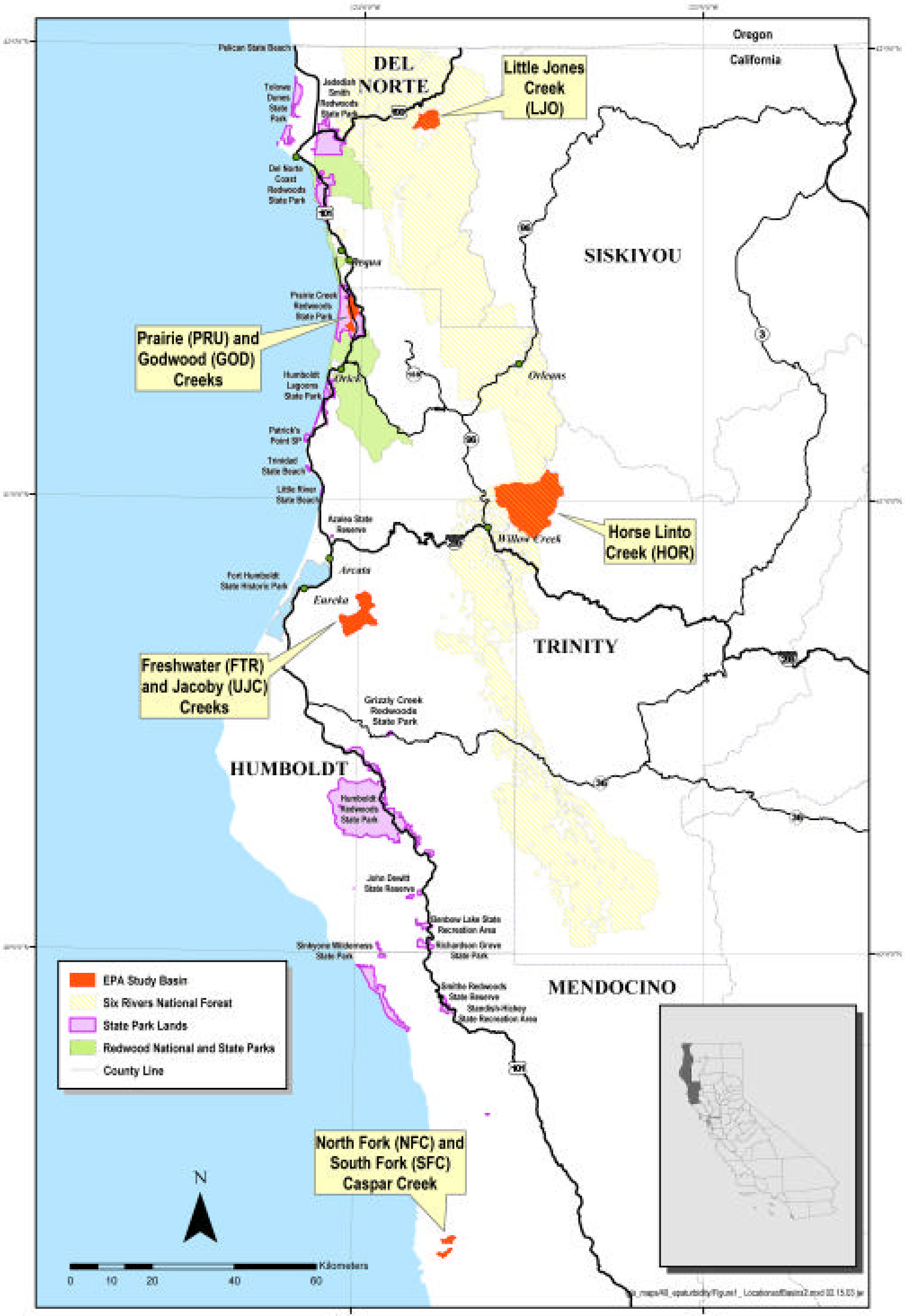


Figure 1. Locations of EPA Study Basins

Data Sources

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

Table 1. Watershed meta-data for EPA study basins.

Stream (Code)	River Basin	Calwater No(s).	Turbidity Data Source*	GIS Data Source(s)*
Little Jones Creek (LJO)	Smith River	1103.300301	USFS-PSW	USFS-6RNF USGS
Horse Linto Creek (HOR)	Trinity River (Klamath R.)	1106.110206 1106.110202	USFS-6RNF	USFS-6RNF USGS
Upper Prairie Creek (PRU)	Redwood Creek	1107.100201	RNSP	USGS RNSP
Godwood Creek (GOD)	Redwood Creek	1107.100201	USFS-PSW	USGS RNSP
Upper Jacoby Creek (UJC)	Humboldt Bay	1110.000504	USFS-PSW	USGS CDF
Freshwater Creek (FTR)	Humboldt Bay	1110.000101 1110.000103	SF/WW	USGS CDF
North Fork Caspar Creek (NFC)	Caspar Creek	1113.300404	USFS-PSW	USGS USFS-PSW
South Fork Caspar Creek (SFC)	Caspar Creek	1113.300404	USFS-PSW	USGS USFS-PSW

*USFS-PSW: US Forest Service, Pacific Southwest Forest and Range Experiment Station, Redwood Sciences Laboratory, Arcata, CA. USFS-6RNF: US Forest Service, Six River National Forest, Eureka, CA. RNSP: Redwood National and State Parks, Arcata, CA. USGS: US Geological Survey. CDF: California Department of Forestry and Fire Protection SF/WW: Salmon Forever/Watershed Watch, Arcata, CA. Timber harvest data for LJO, HOR, PRU, GOD, NFC and SFC represents harvest implementation, whereas timber harvest data for other basins (UJC and FTR) represents harvest plan approval by CDF; implementation may occur up to three years after approval.

Geographical Information System (GIS) data were obtained from several sources (see Table 1) that describe elevations (digital elevation models, or DEMs), vegetation characteristics, roads, timber harvest, and other characteristics. From these data sets, several variables describing watershed characteristics were calculated. An important point to bear in mind when comparing basin characteristics is that both the type of data available and the quality of that data vary among the study basins. For example, road data across the area generally under-represent the true amount of roads on the landscape, and data are more accurate and complete for some areas than others. Similarly, geological mapping varies within the northcoast in terms of the level of detail and whether or not mapping has been digitized.

Basin Characteristics

Table 2 lists physical information about watersheds draining to the eight study streams. While seven of the eight basins fall between about 2 and 15 square miles (mi^2) in drainage area, Horse Linto Creek is substantially larger at 63.8 mi^2. In addition, several other aspects of Horse Linto Creek diverge from the other study basins: 1) the headwaters extend to over 6000 feet in elevation, well within the frequent snow zone, 2) slopes are much steeper, 3) it is located farther inland, and 4) the basin was extensively (73% of the total area) burned by wildfire (the Megram Fire in 1999). To a lesser degree, Little Jones Creek also diverges from the other study basins, particularly in annual precipitation, slope steepness, geology, and elevation range. Only Horse Linto and Little Jones creeks have areas that lie above the common snow line (3000 feet), thus they alone may exhibit runoff processes significantly influenced by snowmelt.

Table 2. Physical characteristics of EPA study basins.

Stream	Drainage Area (mi^2)	Mean Annual Precip. (inches)	Mean Basin Slope (%)	Elev. Range (feet)	Predominant Bedrock Type(s)	Area Above 3000 ft. (%)
Little Jones Creek (LJO)	9.6	100	50.8	1046-4104	Galice Fm. (metased)	12.9
Horse Linto Creek (HOR)	63.8	65	49.5	460-6256	Galice Fm. (metased) and granitic rocks	58.8
Upper Prairie Creek (PRU)	4.1	67	29.1	262-1610	Prairie Creek Fm. marine/fluvial terrace	0
Godwood Creek (GOD)	1.7	67	29.1	154-856	Prairie Creek Fm. marine/fluvial terrace	0
Upper Jacoby Creek (UJC)	5.8	45	38.0	80-2854	Franciscan Fm. melange, Falor Fm. marine terrace	0
Freshwater Creek (FTR)	12.8	45	32.7	764-2382	Yager Fm. And Wildcat Group marine terrace	0
North Fork Caspar Cr (NFC)	1.9	47	35.9	272-1043	Franciscan Fm. sandstone and siltstone	0
South Fork Caspar Cr (SFC)	1.6	47	33.0	131-1086	Franciscan Fm. sandstone and siltstone	0

Geologic composition within the northcoast region contains a broad range of rock types and erosional sensitivities that undoubtedly affect suspended sediment regimes and turbidity duration. However, no universally accepted classification system exists for quantifying erosional sensitivity. Brief descriptions for geology of the eight study basins are given below.

Underlying bedrock in Little Jones (Galice Formation marine slate, metagraywacke and greenstone; Wagner and Saucedo, 1987)) and Horse Linto creeks (Galice Formation in the lower watershed with granitics in the upper watershed) is generally considered to be relatively erosion resistant.

Upper Prairie and Godwood creeks are underlain by the Prairie Creek Formation, consisting of weakly consolidated shallow marine and fluvial sediments of the ancestral Klamath River (Cashman and others, 1995). The basin is crossed by the Lost Man Fault on the eastern slopes of Prairie Creek where a midslope belt of Franciscan rocks (Coherent Unit of Lacks creek) is exposed at the ground surface. The main channel of Prairie Creek as well as its main tributaries (including Godwood Creek) are bounded by recent (Quaternary) alluvial deposits composing low-lying terraces and floodplains.

Upper Jacoby Creek bedrock consists of primarily of Franciscan melange sandstone with areas of Falor Formation sedimentary rocks exposed along the lower segment of the northern slopes (Lehre and Carver, 1985). Earthflows are prevalent within the basin, especially along the northern slopes. Freshwater Creek watershed contains several rock types, including the Yager Formation (interbedded sandstone, siltstone, mudstone, and conglomerate) and the Wildcat Group (interbedded fine sandstone, siltstone, and mudstone) (CGS, 2003) known to be particularly sensitive to disturbance.

The Caspar Creek watershed, including the North and South Fork study basins, lies within the Franciscan Assemblage and is underlain by sandstone and coarse-grained shale (Henry, 1998). Soils are well drained and consist predominantly clay loams.

Figure 2 shows slope distributions for the study basins based on the DEM. As mentioned earlier, Horse Linto and Little Jones creeks diverge in several important ways from the other six study basins. The steepness of these two basins relative to the others is expressed in Figure 2 (e.g., about 50% of the watershed area in Horse Linto and Little Jones creeks was steeper than 50%, while 50% of the slopes in the other basins were only about 30-35%).

Steepland roads and timber harvest, although not the sole causes, have been implicated as primary contributors to elevated erosion and sedimentation in northcoast watersheds. Figure 3 shows road densities in the study basins calculated for the entire contributing area and by slope position (roads located in middle and lower slope positions are generally more prone to erosion). Figure 4 shows the harvest history over the past 30 years as well as areas burned by wildfire since 1988 (Horse Linto Creek was the only basin found to have significant acreage of wildfire).

Figure 3. Watershed slope frequencies for EPA study basins.

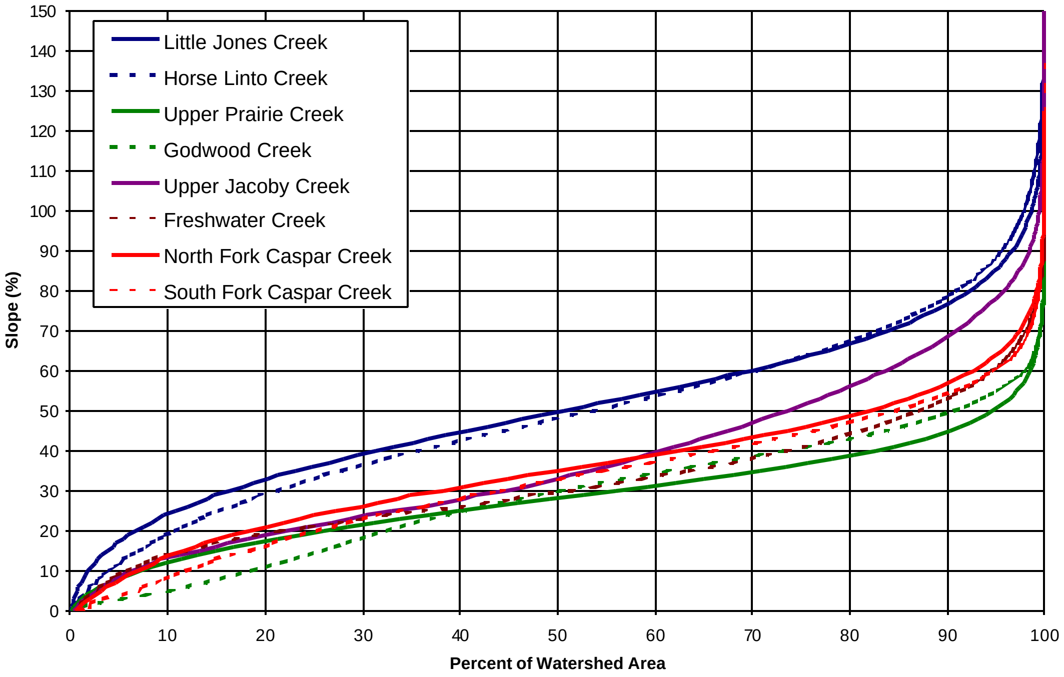


Figure 3. Road Densities in EPA Study Basins

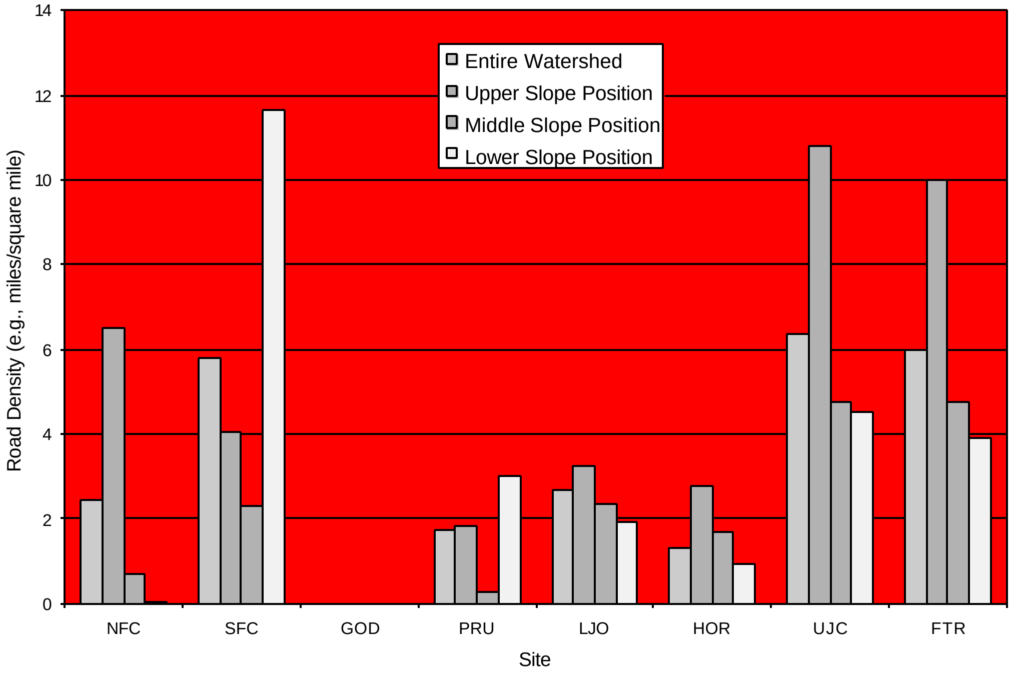
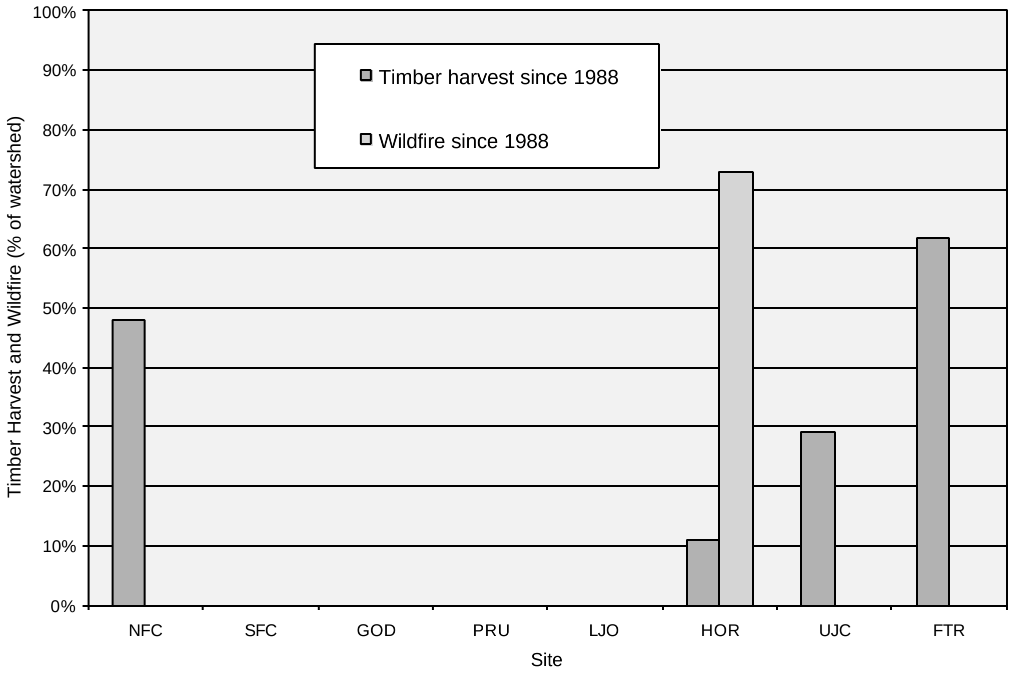


Figure 4. Timber harvest and wildfire history of EPA study basins.



In Appendix A, a series of maps is provided for the study basins with the following themes:

? topography and other features included on USGS quadrangle maps (obtained in digital form),
? 1993 digital orthophotoquads (DOQs),
? shaded relief,
? slope steepness,
? roads and recent (post-1988) timber harvest history, and
? a map of regional average annual precipitation.

For several of the study basins, maps with other themes that were readily available are also included in Appendix A.

METHODS OF DATA COLLECTION AND ANALYSIS

Period of Record Used

Beginning in water year (WY) 2000, the number of recording turbidity stations in operation on the northcoast grew substantially. Consequently, WY2000 was the earliest period used, and WY2002 was the latest period for which data are presently available. Beginning in WY2003 (the current year), several new recording turbidity stations have come on line in the northcoast region. As the period of record and number of stations grows, more robust analyses of turbidity duration and comparisons of different streams in the region will be possible than was the case with this analysis.

Data Collection

Stream stage and turbidity data are recorded at the gaging stations using automated equipment. Data are recorded on 10-minute intervals (essentially continuous) using pressure transducers for stage and optical backscatter-type turbidity sensors (in all cases, the OBS-3 sensor made by D&A Instruments Company) for turbidity [Note: any mention of manufacturers and product names does not constitute endorsement by the federal government]. Occasional discharge measurements are made to relate recorded stages to discharge rate. In most cases, gaging facilities include an electronic pumping water sampler that is controlled by the data logger to sample according to levels of and changes in turbidity or stage. Because this study focused only on turbidity duration, stage data were not converted to discharge, but were plotted as recorded simply to provide a hydrological context for turbidity variations.

The data providers for this study (see Table 1) employ recorded turbidity as a surrogate for suspended sediment concentration (SSC, mg/l) by using what is typically a very strong relationship between the two (although this relationship will vary from stream to stream). Ultimately, suspended sediment yield is estimated from the data by integrating SSC with discharge.

Data Processing

Raw data from the field must be ‘sanitized’ (reviewed and corrected) prior to being considered acceptable for intended uses. The sanitization 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: A) gradually ascending values reflect biofouling by algae growth on the turbidity sensor optics, or B) 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. Most of the data files provided by collecting entities for this analysis had already been sanitized by their own protocols (this includes WY2000 and WY2001 data from USFS-PSW). However, only raw, unsanitized data were provided by USFS-6RNF (HOR site) and Salmon Forever/Watershed Watch (FTR site) and WY2002 data from USFS-PSW had not yet been sanitized. In those cases, it was necessary for me to perform data correction.

Once suspect data were identified, they were scrutinized to determine if an obvious reason for considering them to be erroneous could be identified. In many cases, a single large spike preceded by and followed by a low, nearly constant series of other values could be discarded and replaced with an interpolated value. In other cases, a gradually ascending turbidity value during a period of winter baseflow was confidently considered to be the result of biofouling, especially when it dropped suddenly when the site was serviced and the optics cleaned. In such cases, reliable values could be interpolated for the gradually ascending period.

The most difficult case for treating suspect data occurred when a series of turbidity spikes was encountered that might be unusual in the record, but not implausible. In such cases, a judgement was made based on the appearance of the turbidity plot for the particular storm compared to other storms of similar magnitude occurring the same season. If no means could be determined to confidently correct suspect data, the recorded data were left uncorrected.

In the case of 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, results are 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.

Data Analysis

Turbidity data were analyzed in 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 counting hours. Turbidity levels used in the analyses as class breaks were somewhat arbitrary, although the lowest value appears frequently in the scientific literature as a value above which measurable biological impacts occur (see Introduction). Higher class breaks separate increasingly larger turbidity levels to cover 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. In both cases, only that part of the water year when turbidity is likely to occur (October through the following May, an eight month period) was included. This was done for two reasons: 1) full year data files would have been substantially larger and more unwieldy for analysis, and 2) turbidity sensors are typically removed from the stream for summer low flow periods so they can be recalibrated and are less vulnerable to vandalism.

Finally, results of the turbidity duration analyses were summarized by comparison of turbidities at two turbidity exceedence probabilities: 1% and 10%. While the 1% exceedence includes small to moderate stormflow conditions, the 10% also includes non-storm conditions that better reflect chronic turbidity. Another analysis method would be to perform the more conventional flow duration analysis and examine turbidity levels that occurred during the 1% and 10% flow exceedence probabilities. This was not done because it would require additional data to be acquired and additional analyses that were beyond the scope of this study.

RESULTS

Graphs of turbidity and stage are presented for all available data files in Appendix B. Tables 3-5 give turbidity durations and maximum monthly turbidities for the study streams for WY2000-2003 (note that PRU and UJC did not begin recording turbidity until November, 2000).

Table 3. Turbidity duration and magnitude data for EPA study basins, water year 2000.

Cumulative Hours Above Specified Turbidity (NTU) WY2000							
Stream (Code)	>25	>50	>100	>200	>500	>1000	>2000
Godwood Creek (GOD)	53	4	1	0	0	0	0
Upper Prairie Creek (PRU)	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Little Jones Creek (LJO)	68	31	14	1	0	0	0
Horse Linto Creek (HOR)	167	55	10	5	0	0	0
SF Caspar Creek (SFC)	1749	476	91	26	0	0	0
NF Caspar Creek (NFC)	1177	278	30	1	0	0	0
Upper Jacoby Creek (UJC)	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Freshwater Creek (FTR)	1648	489	143	50	11	0	0

Maximum Turbidity (NTU) WY2000								
Stream (Code)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Godwood Creek (GOD)	n/d	46	9	113	91	33	16	10
Upper Prairie Creek (PRU)	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Little Jones Creek (LJO)	4	23	26	235	33	24	3	22
Horse Linto Creek (HOR)	n/d	95	18	293	92	11	39	29
SF Caspar Creek (SFC)	47	113	53	237	476	69	112	90
NF Caspar Creek (NFC)	119	100	65	132	266	142	56	29
Upper Jacoby Creek (UJC)	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
Freshwater Creek (FTR)	78	500	126	696	628	92	142	138

“n/d” means no data available.

Table 4. Turbidity duration and magnitude data for EPA study basins, water year 2001.

Cumulative Hours Above Specified Turbidity (NTU) WY2001							
Stream	>25	>50	>100	>200	>500	>1000	>2000
Godwood Creek (GOD)	15	3	0	0	0	0	0
Upper Prairie Creek (PRU)	8	2	0	0	0	0	0
Little Jones Creek (LJO)	0	0	0	0	0	0	0
Horse Linto Creek (HOR)	197	30	0	0	0	0	0
SF Caspar Creek (SFC)	402	69	13	0	0	0	0
NF Caspar Creek (NFC)	383	39	6	0	0	0	0
Upper Jacoby Creek (UJC)	159	33	7	1	0	0	0
Freshwater Creek (FTR)	885	249	37	6	0	0	0

Maximum Turbidity (NTU) WY2001								
Stream	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Godwood Creek (GOD)	65	64	28	47	16	34	5	12
Upper Prairie Creek (PRU)	n/d	33	82	13	9	22	26	14
Little Jones Creek (LJO)	9	9	13	7	6	8	14	4
Horse Linto Creek (HOR)	39	38	68	46	31	40	34	17
SF Caspar Creek (SFC)	20	15	66	94	196	91	49	31
NF Caspar Creek (NFC)	51	10	13	51	165	68	20	13
Upper Jacoby Creek (UJC)	n/d	74	73	130	212	81	48	8
Freshwater Creek (FTR)	23	98	153	248	244	257	172	53

“n/d” means no data available.

Table 5. Turbidity duration and magnitude data for EPA study basins, water year 2002.

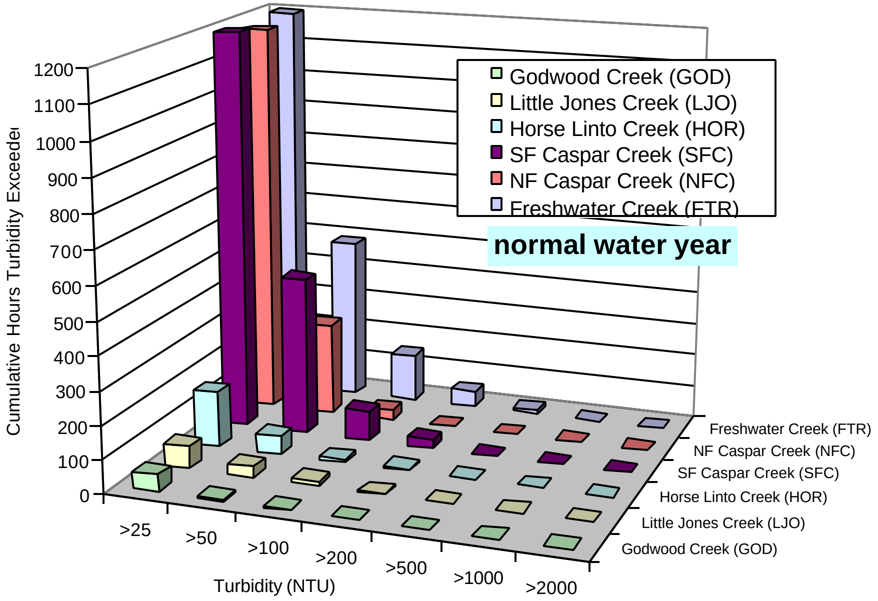
Cumulative Hours Above Specified Turbidity (NTU) WY2002							
Stream	>25	>50	>100	>200	>500	>1000	>2000
Godwood Creek (GOD)	37	8	0	0	0	0	0
Upper Prairie Creek (PRU)	86	17	0	0	0	0	0
Little Jones Creek (LJO)	35	5	0	0	0	0	0
Horse Linto Creek (HOR)	400	188	33	1	0	0	0
SF Caspar Creek (SFC)	679	150	46	10	0	0	0
NF Caspar Creek (NFC)	406	114	28	0	0	0	0
Upper Jacoby Creek (UJC)	985	241	105	53	25	8	2
Freshwater Creek (FTR)	1414	539	221	94	36	20	5

Maximum Turbidity (NTU) WY2002								
Stream	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Godwood Creek (GOD)	25	50	68	32	49	16	15	34
Upper Prairie Creek (PRU)	22	66	93	26	59	8	40	16
Little Jones Creek (LJO)	13	69	45	20	56	7	3	6
Horse Linto Creek (HOR)	18	301	234	150	197	29	60	15
SF Caspar Creek (SFC)	26	217	226	322	248	38	7	7
NF Caspar Creek (NFC)	6	204	109	166	160	21	16	15
Upper Jacoby Creek (UJC)	37	116	2091*	98	298	78	39	10
Freshwater Creek (FTR)	157	781	3690	184	315	227	53	48

* value may reflect debris on turbidity sensor.

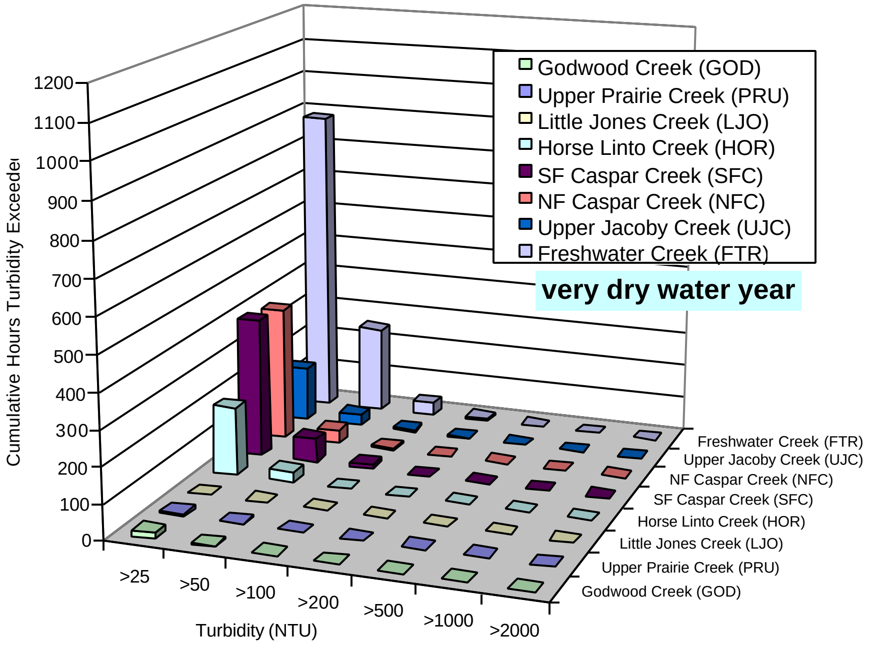
Figures 5-7 show the turbidity duration data from Tables 3-5 graphically.

Figure 5. Turbidity Durations for Six Northcoast Streams: WY2000
(October through May)



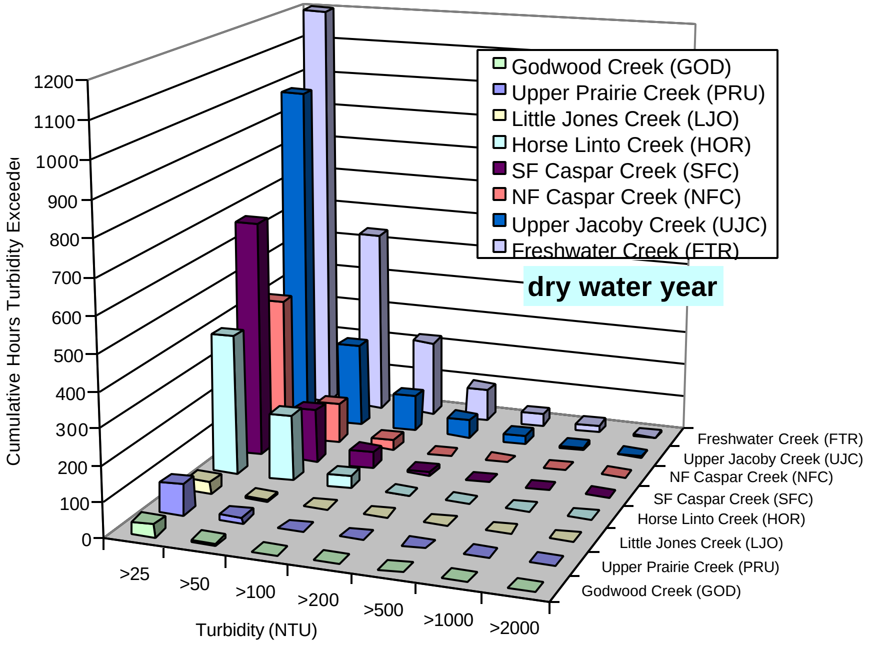
normal water year

Figure 6. Turbidity Durations for Eight Northcoast Streams: WY2001
(October through May)



very dry water year

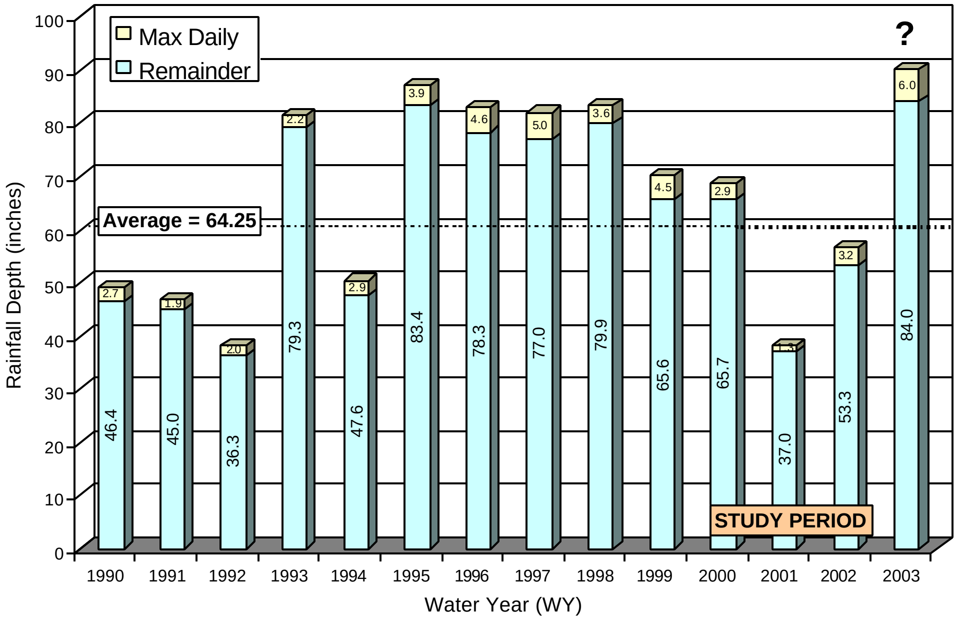
Figure 7. Turbidity Durations for Eight Northcoast Streams: WY2002
(October through May)



As noted on Figures 5-7, each of the three water years had different climatological conditions (WY2000 was normal, WY2001 was very dry, and WY2002 was dry). These classifications are based on rainfall measured in Prairie Creek, as shown in Figure 8. Although rainfall depth certainly varied across the northcoast during the three years analyzed here, the climatological classes hold across all study basins. Note that the maximum daily rainfall is shown at the top of each bar in Figure 8. This is provided as an index of the largest turbidity-producing storm of the period, as peak runoff conditions are not well represented by total annual rainfall.

Obviously, turbidity magnitude and duration will vary from year to year with the amount of rainfall that occurs and the temporal distribution of that rainfall. As shown on Figure 8, rainfall was about normal for WY2000, the first year of turbidity duration analysis. Further, the maximum daily rainfall (2.9 inches) was very near the mean for the 1990-2002 period as well (3.1 inches). However, in WY2001, annual rainfall was very low (only a little more than half the average of 64.25 inches) and maximum daily rainfall (1.3 inches) was less than half of average (3.1 inches). Annual rainfall in WY2002 was still below normal, but maximum daily rainfall (3.2 inches) was about normal. Though not yet complete as of this writing, a projection based on year-to-date rainfall for WY2003 is shown on Figure 8 (130% of normal).

Figure 8. Annual and maximum daily rainfall depths for Prairie Creek, WY1990-2002



Turbidity durations shown in Tables 3-5 and Figures 5-7 generally reflect the climatological differences between the three years (lower durations in drier years). An exception is the long duration that turbidity exceeded 25 NTU in Freshwater Creek (FTR) in WY2002 (see Fig. 7) relative to the other streams, considering it was a dry year. As shown in Tables 3 and 5, turbidity exceeded 25 NTU for 1648 hours and 1414 hours for WY2000 (a normal year) and WY2002 (a dry year), respectively.

Table 6 summarizes turbidities at the 1% and 10% exceedence probabilities over the three water years. As indicated in Figures 9-11, the 1% exceedence probability corresponds to about 2.4 days (58.3 hours) for the eight-month study period and the 10% exceedence probability corresponds to about 24 days (583 hours). While the 1% exceedence includes small to moderate stormflow conditions, the 10% exceedence probability also includes between-storm baseflows and so provides a better index of chronic turbidity levels.

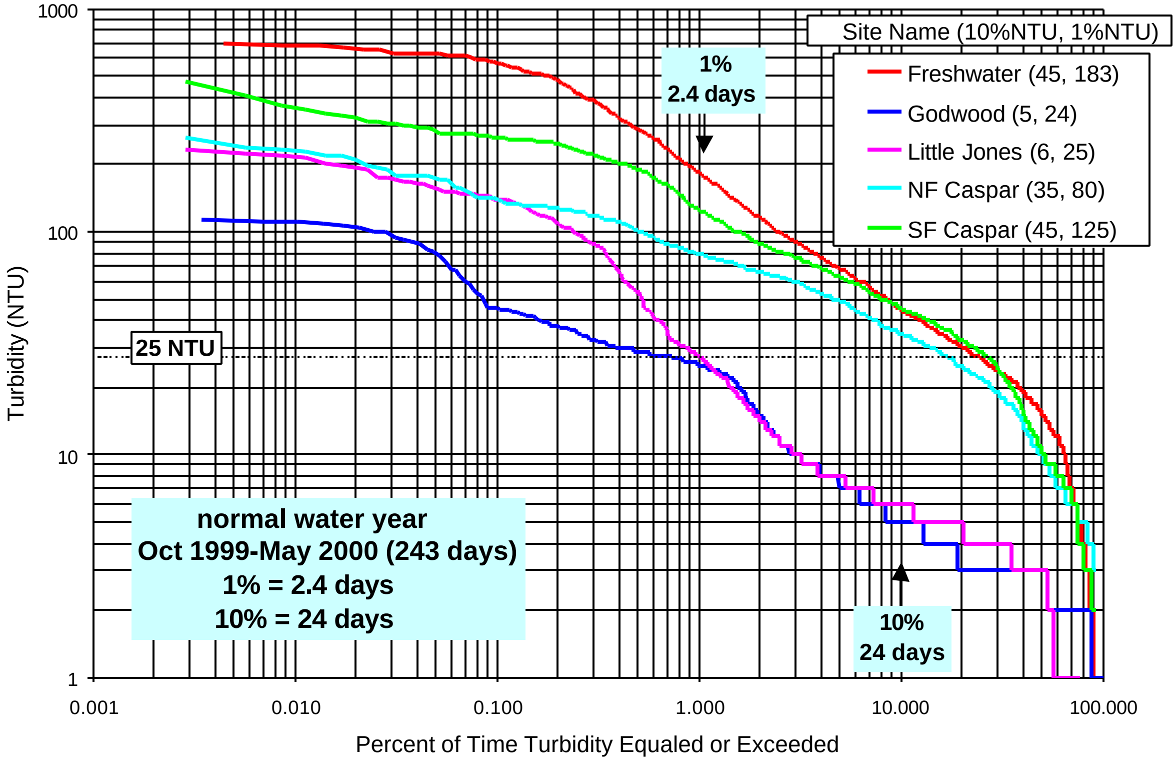
As indicated in Table 6, turbidities in some streams were many times greater than in others. For example, in WY2000 (a normal rainfall year), Little Jones and Upper Prairie creeks had similarly low turbidities at the 10% exceedence (6 and 5 NTU, respectively), but turbidities in Freshwater Creek and North and South Forks Caspar creeks were 9, 7, and 9 times greater, respectively. Similar differences existed for WY2001. In WY2002, mean turbidity at the 10% exceedence for the three cleanest streams (Little Jones, Upper Prairie, and Godwood creeks) was about 7 NTU, but was about 32 NTU for the four most turbid streams (Upper Jacoby, Freshwater, and North and South Forks Caspar creeks), or more than four times greater.

Table 6. Turbidities at the 1% and 10% exceedence probability for the EPA study streams, WY2000-2002.

Stream (code)	**NTU, WY2000**		**NTU, WY2001**		**NTU, WY2002**	
	1% Ex. Prob.	**10% Ex. Prob.**	**1% Ex. Prob.**	**10% Ex. Prob.**	**1% Ex. Prob.**	**10% Ex. Prob.**
Little Jones Creek (LJO)	25	6	5	3	19	4
Horse Linto Creek (HOR)	n/d	n/d	47	18	84	20
Upper Prairie Creek (PRU)	n/d	n/d	18	4	35	11
Godwood Creek (GOD)	24	5	11	4	21	7
Upper Jacoby Creek (UJC)	n/d	n/d	46	18	189	31
Freshwater Creek (FTR)	183	45	83	33	303	49
North Fork Caspar Creek (NFC)	80	35	47	16	68	20
South Fork Caspar Creek (SFC)	125	45	52	19	85	26

"n/d" means no data available.

Figure 9. Turbidity exceedence curves for EPA study basins, WY2000



1%
2.4 days

10%
24 days

normal water year
Oct 1999-May 2000 (243 days)
1% = 2.4 days
10% = 24 days

Figure 10. Turbidity Exceedence Curve for EPA Study Basins, WY2001

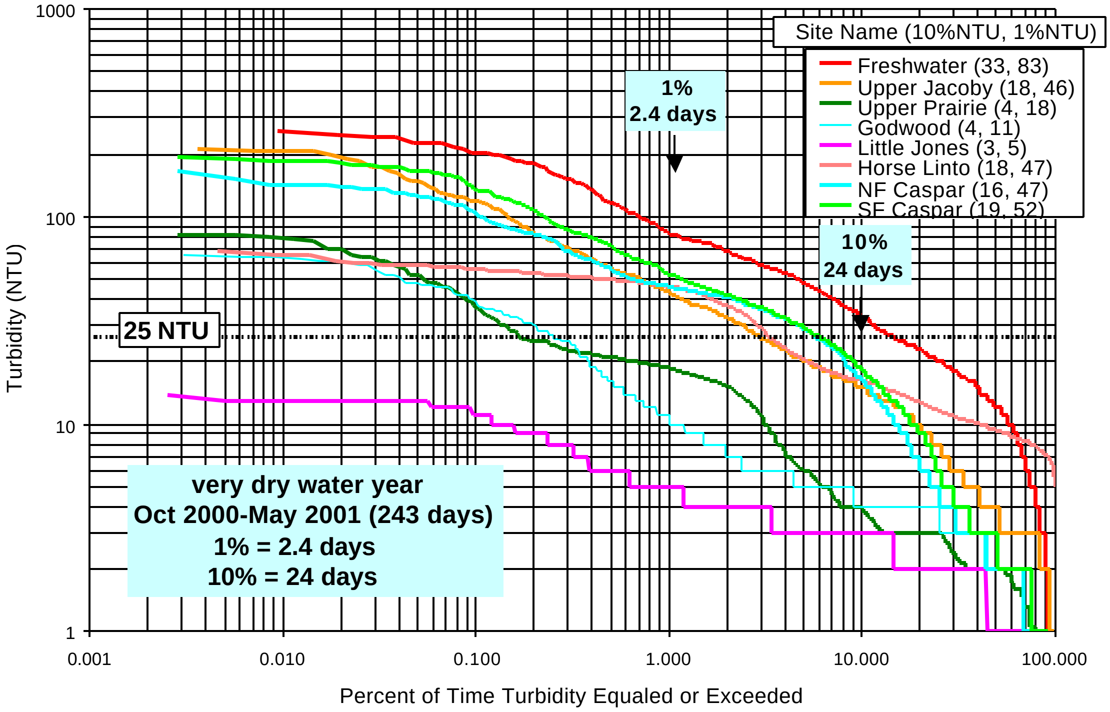
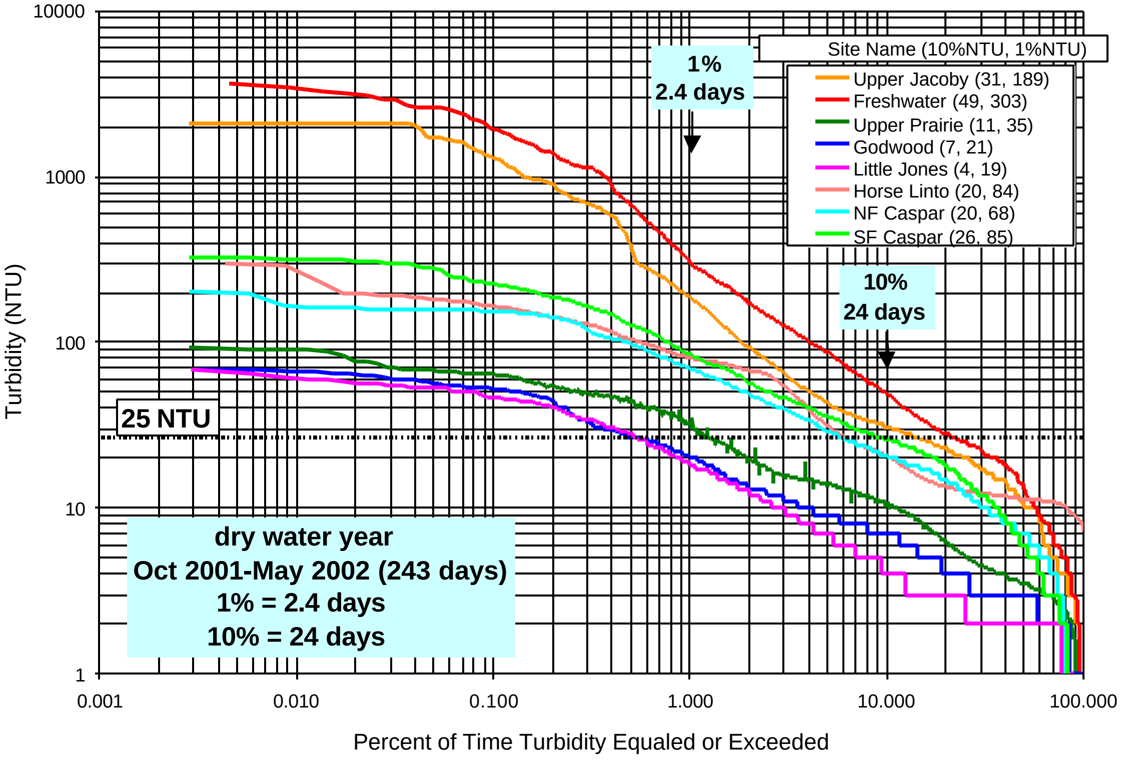


Figure 11. Turbidity exceedence curves for EPA study basins, WY2002



Figures 12 and 13 show relationships between the 10% exceedence turbidity for WY2002 and annual rate of timber harvest (1988-2002) and road density, respectively. Individually, these two land management variables explained fair amounts of the variability in turbidity at the 10% exceedence level (as indicated by their R-squared values), and did so in a logical manner, i.e., turbidity increased as a function of both the density of roads in a watershed and the annual rate of timber harvest.

Figure 12. Annual harvest rate since 1988 and 10% turbidity exceedences for WY2002 (site codes identify data points)

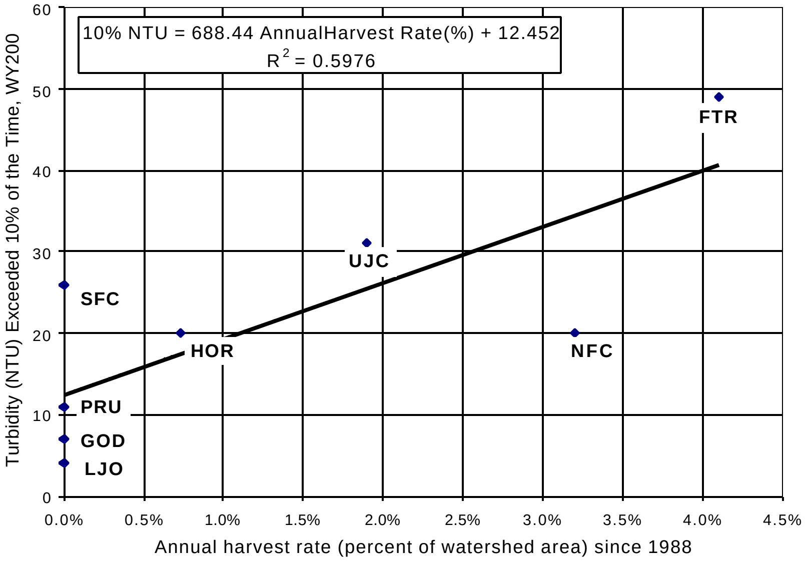
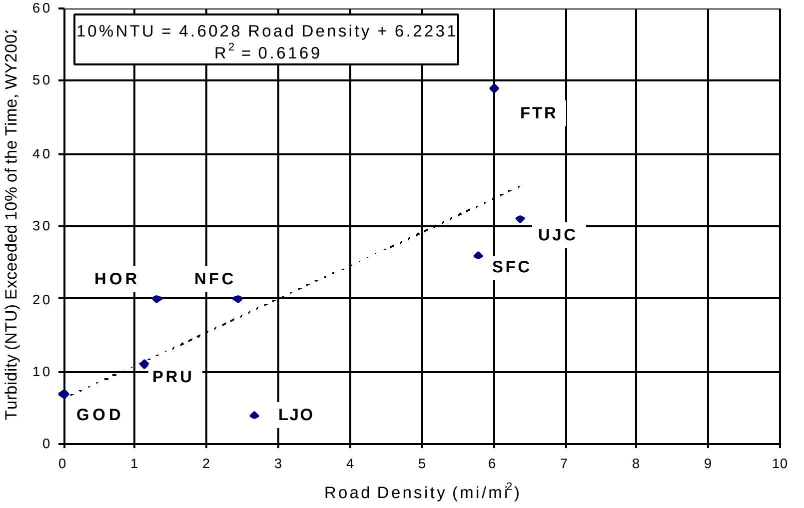


Figure 13. Road densities and turbidity exceedences for WY2002 (site codes identify data points)



To examine the combined effect of these two variables on turbidity, a multiple linear regression analysis was performed using WY2002 data. This water year was selected over for regression analysis because: 1) in WY2000 only five of the eight turbidity stations were in operation, and 2) WY2001 was a very dry year, thus it was less representative of normal conditions than WY2002.

Regression output is given in Appendix C. This simple two-variable model explained over 75% of the variability in turbidity at the 10% exceedence level (adjusted R-squared = 0.752, see Appendix C). Road density as a predictor of 10% turbidity exceedence was slightly less than significant at the 95% confidence level (P-value = 0.0478). Annual harvest rate was significant at the 95% level (P-value = 0.0607). As mentioned earlier, data acquired on roads was inconsistent in quality and completeness between the study basins, and this may explain the relatively lower level of significance for road density in the regression. The predicted 10% turbidity exceedence for Horse Linto Creek had the largest standard residual, indicating larger disagreement between the observed and predicted values than for the other basins. As mentioned earlier, Horse Linto Creek was heavily burned in 1999, just prior to the data period used for this analysis. Post-fire erosional responses are a likely explanation for the larger standard residual.

Although not chosen as a class break in this study, turbidity durations above 150 NTU were also determined. This is given as a threshold for juvenile chinook salmon in Gregory and Northcote (1993). They found in laboratory experiments that foraging for surface and benthic prey by juvenile chinook was generally greatest between 35 and 150 NTU, with feeding dropping precipitously above about 150 NTU. For planktonic prey, feeding substantially declined above about 70 NTU. Table 7 lists the cumulative hours 150 NTU was exceeded for each of the three water years. As with other turbidity levels presented in Tables 3-5, Freshwater Creek was far and away the most turbid of the eight study streams. In some cases, 150 was never exceeded during the winter period, particularly in Godwood Creek. Even in Horse Linto Creek, nearly three-quarters of which was burned in the Megram Fire of 1999, 150 NTU was not exceeded in WY2001, and was only exceeded in WY2002 for less than 1/20th the time that it was exceeded in Freshwater Creek.

Table 7. Turbidity durations (cumulative hours) above 150 NTU for EPA study basins, water years 2000-2002.

Stream (code)	**Cum. Hours >150 NTU WY2000**	**Cum. Hours >150 NTU WY2001**	**Cum. Hours >150 NTU WY2002**
Little Jones Creek (LJO)	3.7	0	0
Horse Linto Creek (HOR)	n/d	0	6.3
Godwood Creek (GOD)	0	0	0
Upper Prairie Creek (PRU)	n/d	0	0
Upper Jacoby Creek (UJC)	n/d	2.0	73.7
Freshwater Creek (FTR)	77	16.5	132
SF Caspar Creek (SFC)	45	4.8	23
NF Caspar Creek (NFC)	4.2	0.3	9.2

DISCUSSION

The analyses conducted here demonstrate that turbidity duration characteristics can vary widely among northcoast streams. This is no significant finding in and of itself, owing to the variability of geological and climatic conditions within the region. However, durations of turbidities at several levels (the lowest being 25 NTU) spanned up to two orders of magnitude for the streams analyzed here. In addition, the 10% exceedence turbidity for the part of the year when turbidity would be expected to occur (October through the following May) varied directly and strongly with two important land use variables: road density and recent (post-1988) timber harvest rate expressed as an annual percentage of basin area.

Defining 'Background'

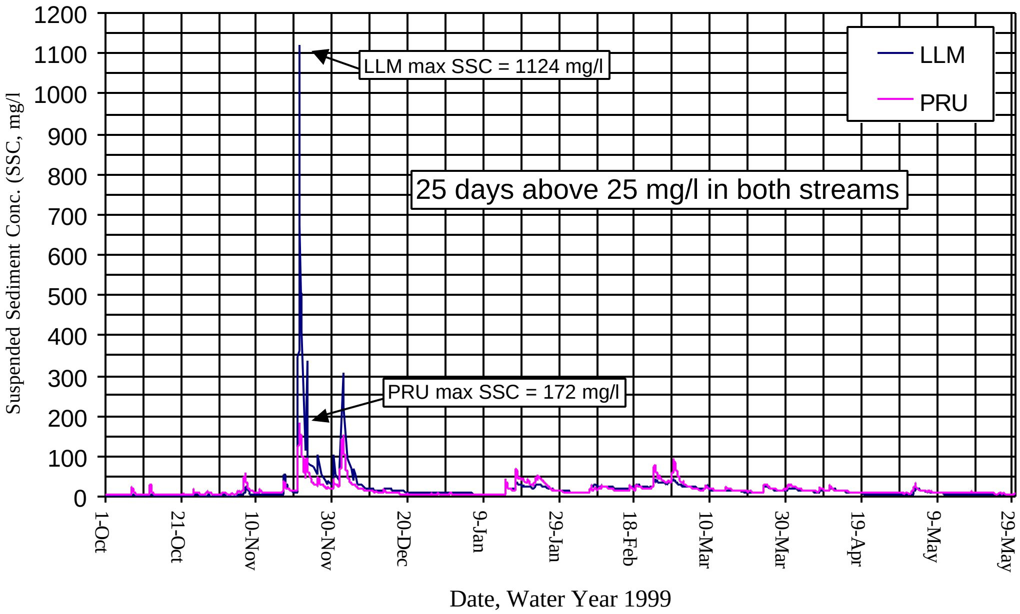
A nagging question preventing establishment of defensible water quality standards for parameters such as turbidity or suspended sediment is "what is background?" Intrinsic (i.e., natural factors such as soils, geology, steepness, etc.) differences between watersheds, even those in close proximity to one another, likely account for substantial variability in suspended sediment concentrations (SSC) and yield. The multiple regression analysis showed that roads and recent timber harvest rate exert strong control over turbidity duration. However, the value of the regression analysis was not to provide a quantitative model of the roles of roads and timber harvest on turbidity duration for the northcoast (a larger number of recording turbidity stations would be required for this). Rather, the value is in demonstrating that: 1) roads and annual timber harvest rate are major influences on turbidity duration, and 2) despite the substantial variations in rainfall, geology, topography, and other intrinsic watershed characteristics across the north coast, this 'system noise' is not so overwhelming as to render definition of background conditions and assessment of the role of management a hopeless endeavor.

In support of this, data from several northcoast streams suggest that: 1) intrinsic differences between watersheds are primarily expressed in peak or near-peak suspended sediment concentrations that occur during moderate to large storms, and 2) for most of the winter runoff period (late in the recessional limb of moderate to large storms, during small storms, and during winter baseflow conditions), undisturbed watersheds, even those with very different soils, geology, and steepness, tend to have similarly low turbidity and SSC durations. This is based on field observations and data collected in several small, relatively pristine watersheds within Redwood National and State Parks (the Prairie Creek basin): Little Lost Man Creek (LLM) and Prairie Creek above Brown Creek (PRU). Figure 14 presents sedigraphs (suspended sediment concentration over time) for LLM and PRU for water year 1999.

Although located within a few miles of each other, virtually identical in watershed area, and subject to the same climatic and tectonic setting, the LLM and PRU watersheds are quite different in their soils, geology, and slope steepness. LLM is underlain by the "Coherent sandstone and mudstone unit of Lacks Creek" ("KJfl", Cashman and others, 1995), consisting of interbedded graywacke sandstone and mudstone. Hillslopes are relatively steep in LLM and the main channel of the creek appears to follow an unmapped fault lineament parallel to regional northwest structural trends. Inner gorge slopes are quite steep along the main channel lineament and streamside landslides are prevalent. Accordingly, I characterize the LLM watershed as relatively erodable with respect to intrinsic factors (a relatively 'dirty' pristine stream).

In contrast, the PRU watershed is underlain predominantly by the Prairie Creek Formation ("QTpc", Cashman and others, 1995), consisting of fluvial and marine sediments. Exceptions are found in the valley bottomlands, where Quaternary alluvium bounds the stream channel, and near the eastern divide, a belt of KJfl has been mapped (Cashman and others, 1995). Slopes are relatively gentle in PRU (mean basin slope is 29%, see Table 2) and active streamside landslides are virtually non-existent. Thus by comparison with LLM, PRU can probably be characterized as a less erodable watershed (a relatively 'clean' pristine stream).

Figure 14. Water year 1999 sedigraphs for two unmanaged northcoast streams: Little Lost Man Creek (LLM: DA = 3.46 mi^2) and Prairie Creek above Brown Creek (PRU: DA = 4.02 mi^2)



The period shown in Figure 14 predates deployment of a turbidity sensor at PRU, so sedigraphs are presented here instead of turbidigraphs. The sedigraphs were constructed by using automated suspended sediment samples taken of the winter period (Oct-May) from stage-based sampling protocols and estimating SSC for intervening non-sampled periods. Estimation methods included interpolation for relatively short time periods between samples and using storm-specific rating curves, methods consistent with those used by the USGS.

Although LLM and PRU are both virtually pristine, about the same size, and subject to essentially the same rainfall and tectonic setting, peak SSC varied substantially (1124 mg/l for LLM and 172 mg/l for PRU, Fig. 14). I attribute this to intrinsic differences in erodability, as discussed above. However, as shown in Figure 14, both streams had the same duration (25 days) of SSC above 25 mg/l. From this, I infer that although intrinsic differences in physical basin attributes that determine erodability can cause large differences in SSC at peak stormflows, SSC at other times (small storms, large storm recessional flows, and winter baseflows; the primary hydrographic components potentially contributing to chronic turbidity) is much less affected by intrinsic watershed variability. Thus it has potential to be used as a diagnostic tool for quantifying management effects and circumventing the age-old problem of defining background conditions. Should this hypothesis hold following more comprehensive studies than that done here (more streams, more years of data), then expressions of chronic turbidity (e.g., the 10% exceedence NTU) will have good potential for setting robust water quality standards.

Implications for watershed management

The results suggest that land management is having dramatic effects on durations of turbidity above the thresholds examined here, and that turbidity levels might be decreased by: 1) reducing the density of roads in a watershed, and 2) limiting the annual rate of timber harvest. However, these results should be considered preliminary and not be used alone for policy decisions or regulatory standards.

To cost-effectively target management actions and/or constraints to reduce chronic turbidity and suspended sediment concentrations to acceptable levels, we must first identify the main sources and land use practices responsible. Are they derived from: 1) current practices, such as winter use of roads, broadcast burning, tractor yarding, and increased landsliding from tree removal, 2) fresh erosion on relict features from past land uses, such as old, abandoned roads, landings and skid trails, 3) secondary erosion processes (surface, rill, and gully erosion) on active landslides, 4) remobilization of fine sediment contained in flood terraces deposited in the 1964 and other large floods, or 5) particle attrition as bedload-sized material moves downstream? All these sources are management-related and are likely contributing to chronic turbidity, but only by determining their relative importance will cost-efficient mitigations be possible.

The results of this analysis, although based on a small sample size (8 streams), suggest that chronic turbidity is closely tied to recent timber harvest (since 1988 in this study) and, by inference, less dependent on ‘legacy’ conditions. This argues for quantitative limits on annual harvest rates, perhaps customized to accommodate the variability in erosional sensitivity found within the northcoast. But a stronger analysis, one that includes a greater sample size of northcoast streams, is needed to establish defensible harvest rates that ensure protection of beneficial uses.

To better quantify management effects, it is imperative to identify and monitor turbidity in representative sample of basins that capture the range of intrinsic and management-related characteristics found within the north coast region. Basins that have not been managed (extremely rare) and basins that have recovered from historical logging (e.g., advanced second growth watersheds) can serve as reference sites. Such basins should be set aside and reserved for collection of baseline data and, assuming other habitat elements are in reasonably good condition, would also serve as refugia. State and federal parklands likely offer the best potential for augmenting the number of recording stations for characterizing baseline turbidity and suspended sediment concentrations.

It is encouraging to note that, as of this writing, several new continuous turbidity stations are operating on northcoast streams beyond the eight used in this study. These include Lost Man and Little Lost Man creeks in Redwood National and State Parks, Lower Jacoby Creek, North and South Forks of Elk River, and others located on private timberlands in Humboldt County and perhaps elsewhere in the northcoast. A far more comprehensive assessment of chronic turbidity will soon be possible if data from a greater number of sites can be pooled.

RECOMMENDATIONS

The following recommendations are given for consideration:

Utilize the growing number of recording turbidity stations on the northcoast in a more comprehensive assessment

As indicated above, supplemental analyses of turbidity duration characteristics using a greater number of sites holds promise to refine our understanding of the role of management in chronic turbidity, and this analysis is the foremost recommendation given here. Certainly, the conclusions of this study must be considered preliminary because of the small sample size used, but this was unavoidable. If made a funding priority, more turbidity recording stations than exist today are feasible and will help to better define both background conditions and management effects.

Perform additional analyses on turbidity and flow duration beyond those done here

Other ways of analyzing turbidity data beyond those used in this study may prove superior and should be explored. For example, examining turbidity levels at various discharge exceedences may also provide insights into the role of land management. The value of such an analysis is that many more stream gaging stations have continuous stage recording than those with stage and turbidity. Consequently, defining an ‘acceptable’ turbidity limit based on a flow exceedence value is more likely to provide a practical regulatory standard than relying only on streams with recording turbidity equipment. With a stage-discharge rating curve, discharge can be calculated and, from that, flow duration analyses performed (flow duration analyses are possible for the sites used in this study, but would have required more analysis than the scope of the project allowed). Then, a flow exceedence value can be targeted for turbidity and suspended sediment sampling, allowing flow-targeted grab sampling to provide comparative turbidity data for many streams without the need for recording of turbidity at each one. Caveats in this effort will be the sometimes-weak relationship between streamflow rate and turbidity or suspended sediment concentration (i.e., suspended sediment rating curve) and effects of steepland roads and timber harvest on peak stormflows and low flows.

Augment recording stations with grab sampling at upstream locations

While collecting turbidity at the outflow point of a watershed can provide a good idea of conditions within the watershed, it does little to inform management of where problems are originating or what sorts of practices tend to exacerbate chronic turbidity more than others. Consequently, supplementing data from the watershed outflow point with occasional sampling from locations within the watershed can, with little additional expense, provide a far more useful data set. This type of sampling lends itself to use of volunteers, so long as they are dedicated, well trained, and provided with technical oversight.

Improve GIS coverages on timber harvest, roads, and geology

As discussed earlier, GIS data were obtained from several different entities for this analysis and varied in coverage and completeness. Consistent and complete GIS data on important themes such as timber harvest, roads, geology, and others, across all north coast watersheds will is needed to more confidently quantify the roles of these variables in downstream water quality and set appropriate limits on timber harvest rates and road densities.

Initiate biological monitoring at recording turbidity sites

Finally, because turbidity in and of itself is not the central issue of concern, rather it is the beneficial uses that stand to be impaired by turbidity, biological studies are needed to further our understanding of turbidity impacts, particularly in field situations. The turbidity stations now in operation afford a tremendous opportunity to co-locate with biological studies and provide insights into both sides of the issue.

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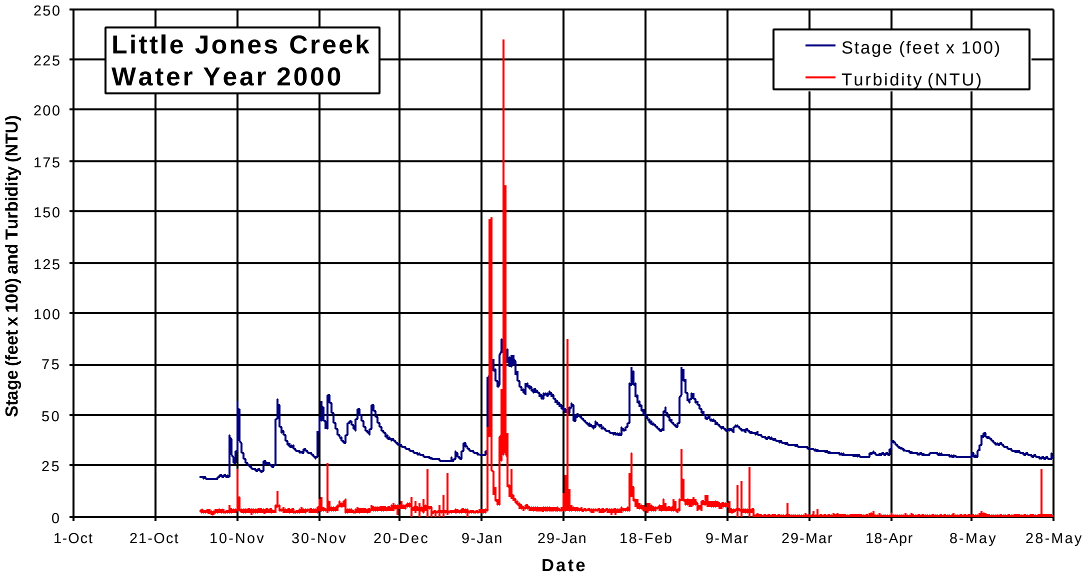
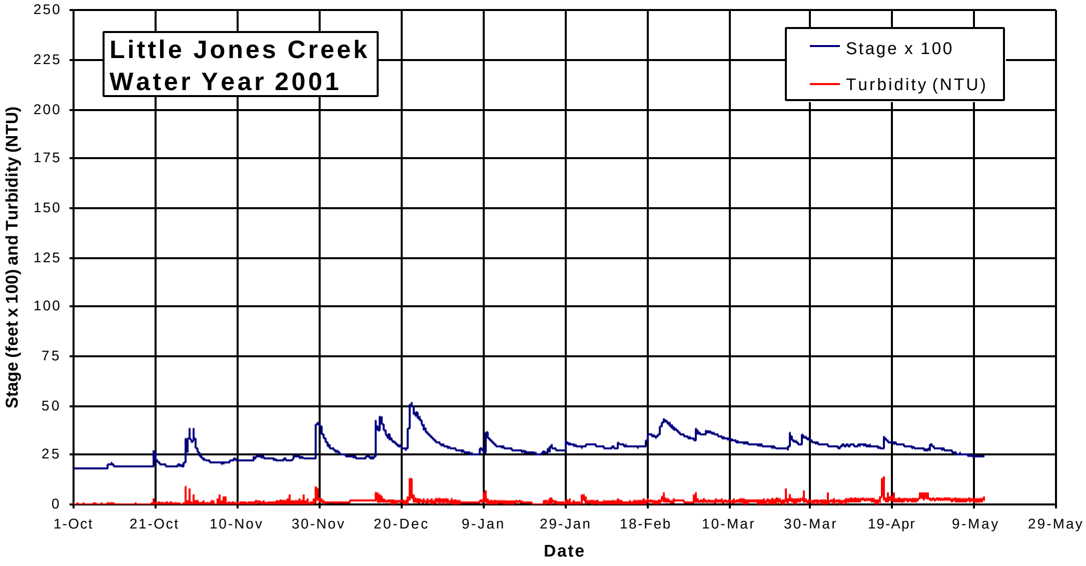
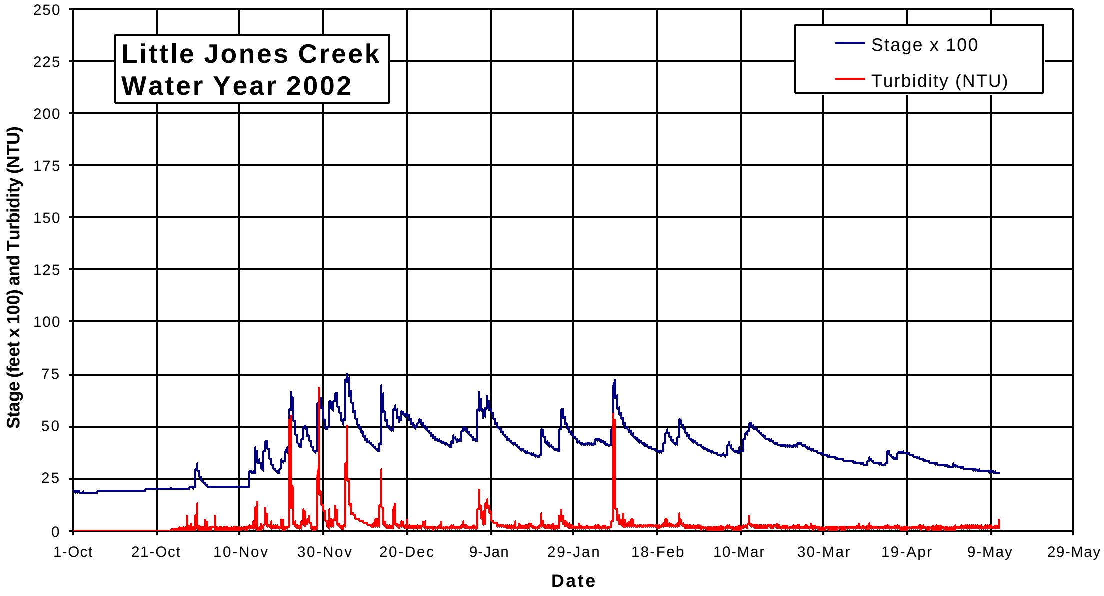
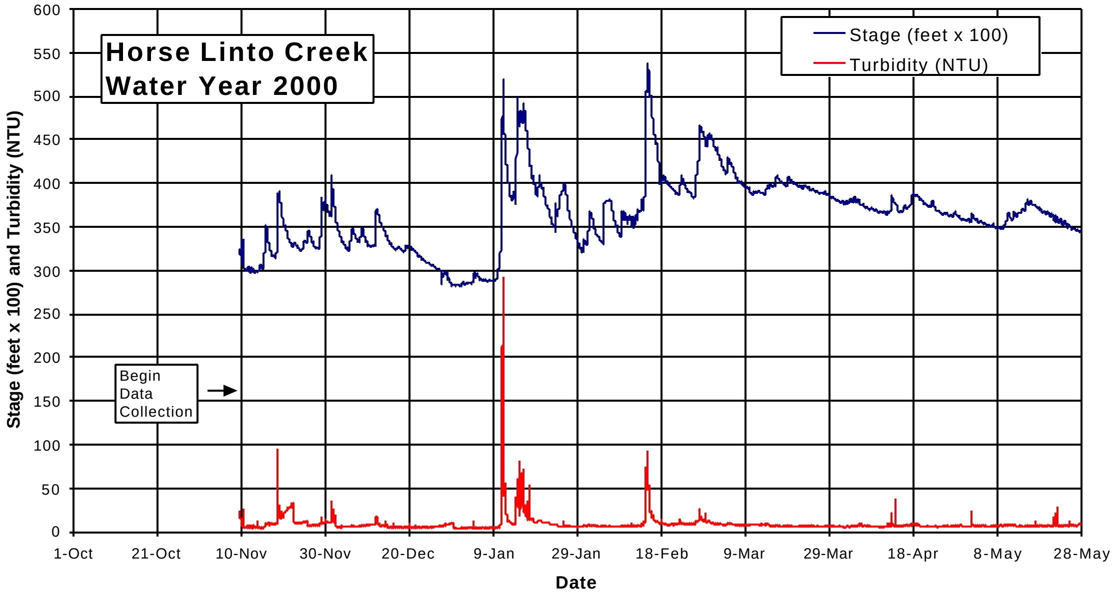
APPENDIX A: MAPS OF EPA STUDY BASINS

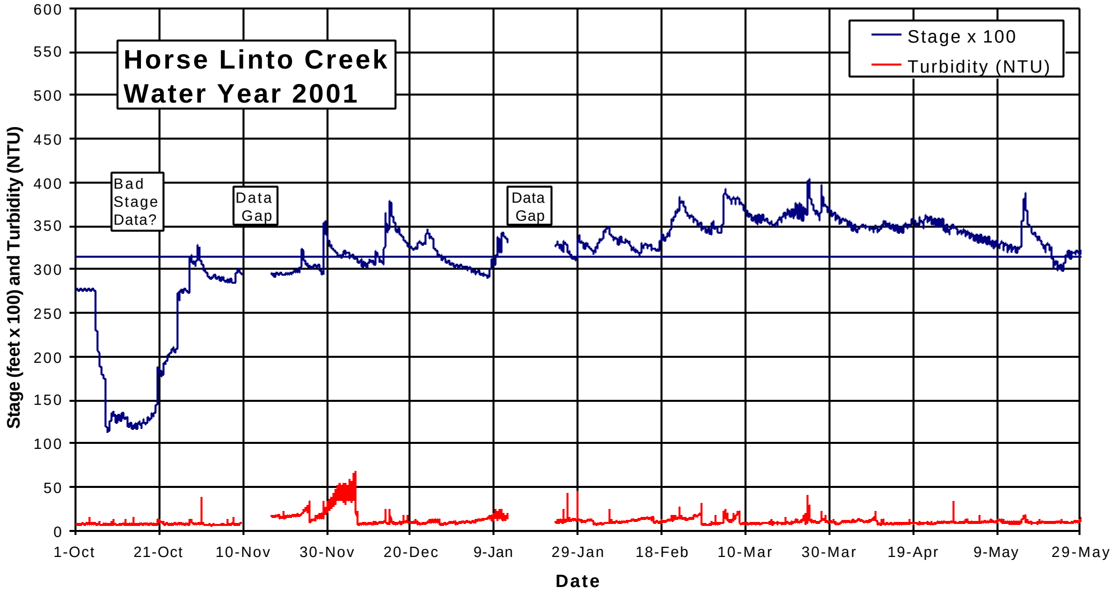
APPENDIX B: TURBIDIGRAPHS FOR EPA STUDY BASINS

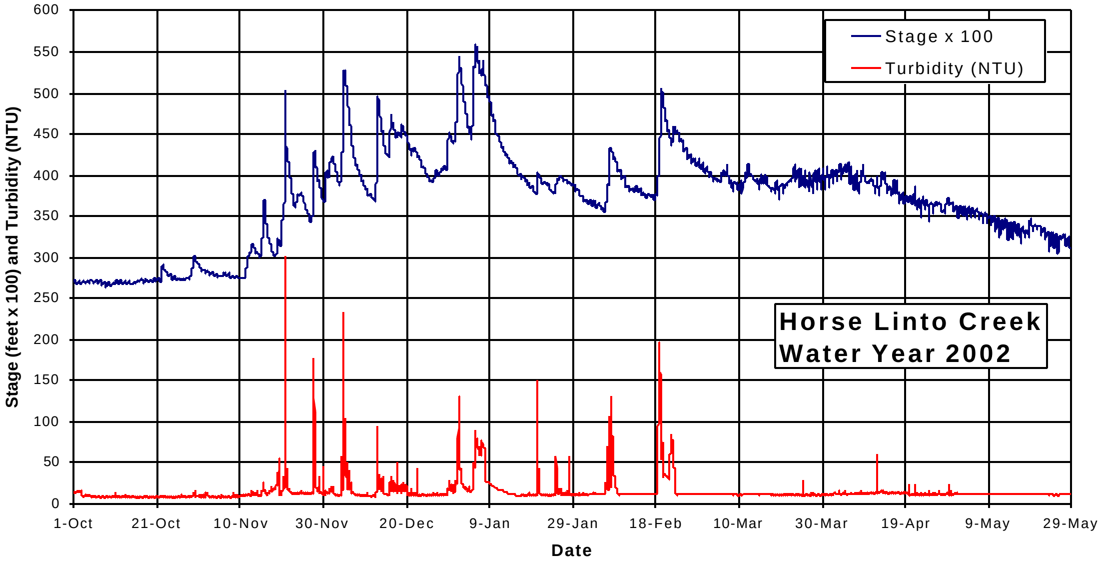

Little Jones Creek
Water Year 2000
Stage (feet x 100)
Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
250
225
200
175
150
125
100
75
50
25
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
9-Mar
29-Mar
18-Apr
8-May
28-May
Date

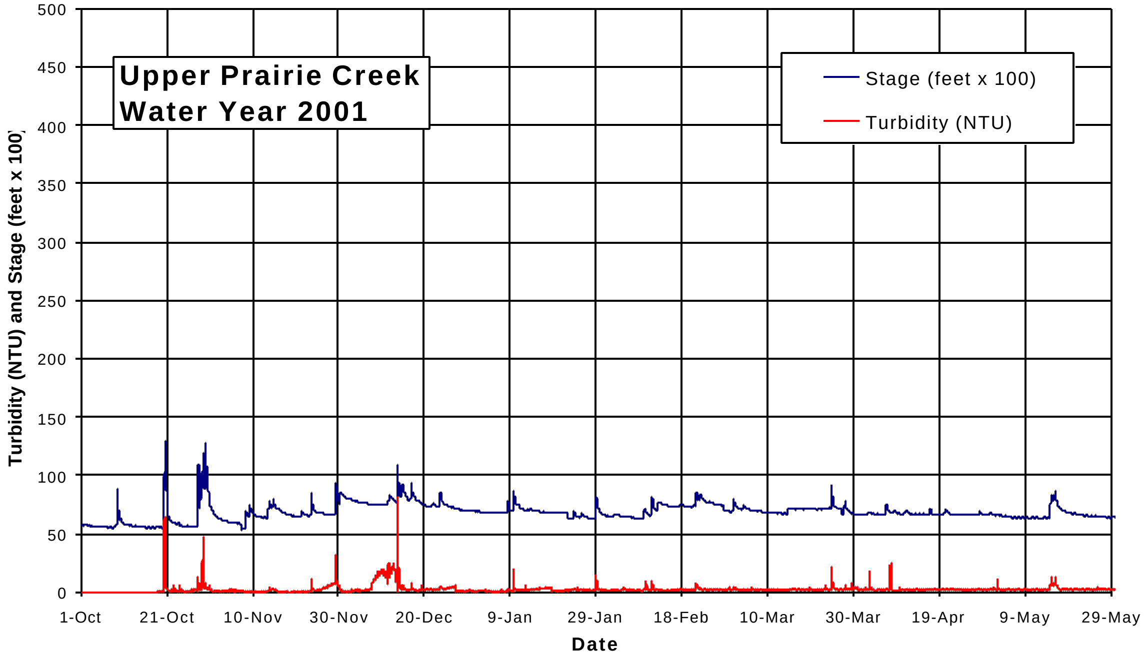

Little Jones Creek
Water Year 2001
Stage x 100
Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
250
225
200
175
150
125
100
75
50
25
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

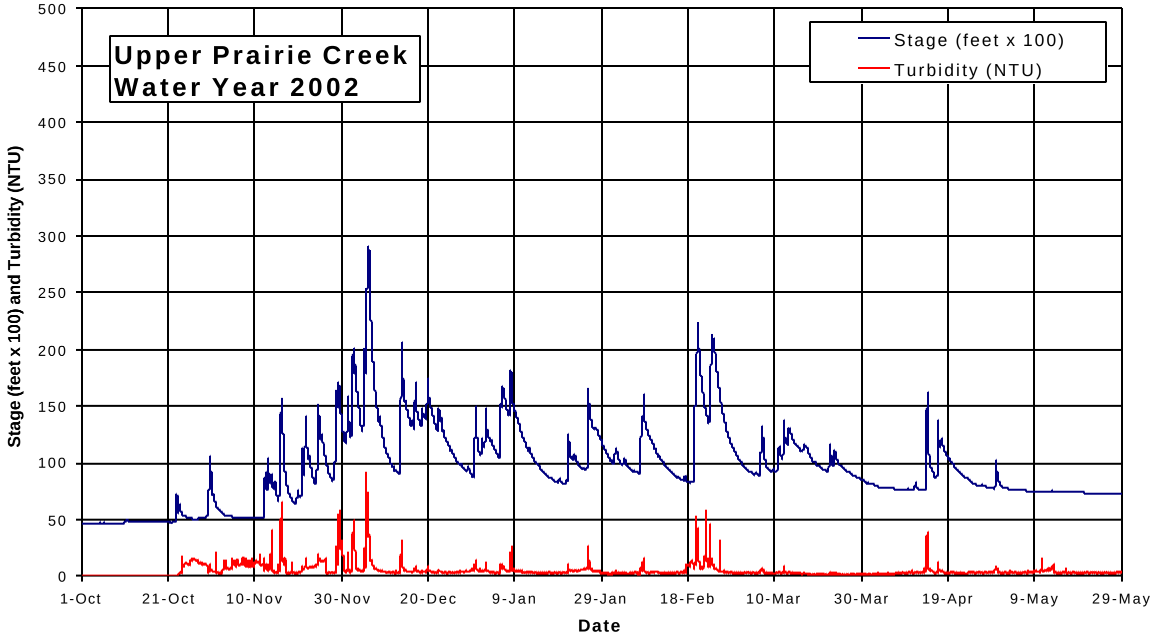

Little Jones Creek
Water Year 2002
Stage x 100
Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
250
225
200
175
150
125
100
75
50
25
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

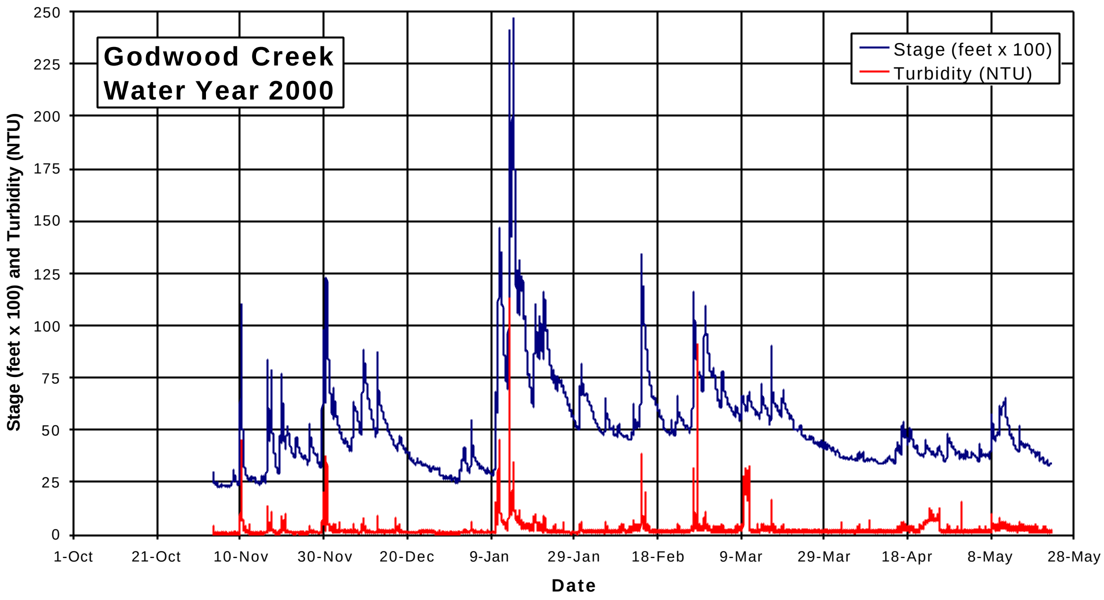

Horse Linto Creek
Water Year 2000
Stage (feet x 100)
Turbidity (NTU)
Begin
Data
Collection
Stage (feet x 100) and Turbidity (NTU)
600
550
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
9-Mar
29-Mar
18-Apr
8-May
28-May
Date

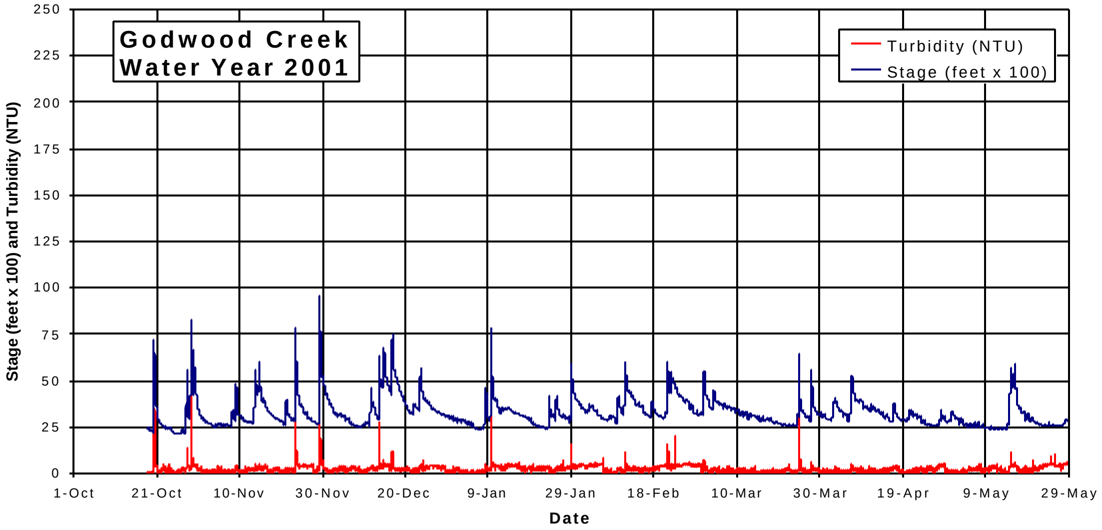

Horse Linto Creek
Water Year 2001
Stage x 100
Turbidity (NTU)
Bad
Stage
Data?
Data
Gap
Data
Gap
Stage (feet x 100) and Turbidity (NTU)
600
550
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

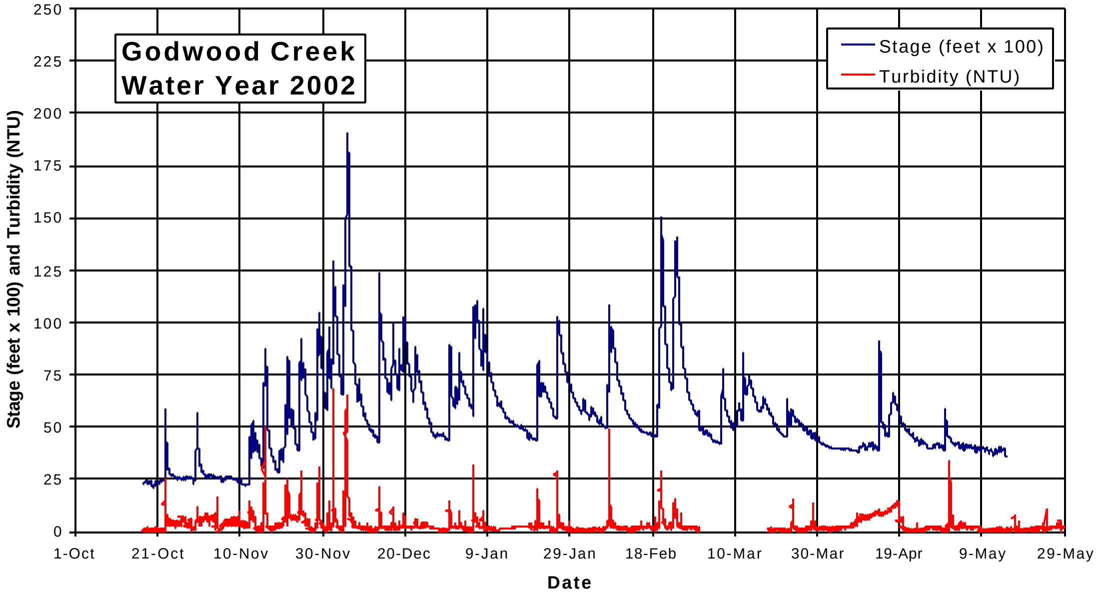

Stage x 100
Turbidity (NTU)
Horse Linto Creek
Water Year 2002
Stage (feet x 100) and Turbidity (NTU)
600
550
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

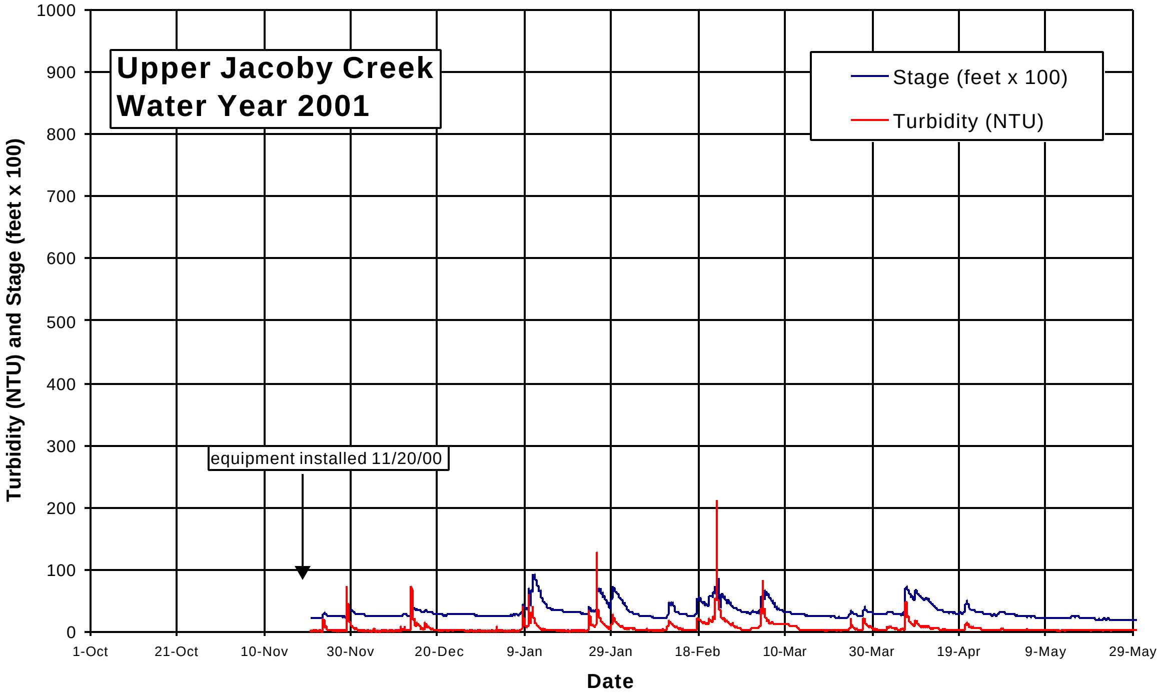

Upper Prairie Creek
Water Year 2001
Stage (feet x 100)
Turbidity (NTU)
Turbidity (NTU) and Stage (feet x 100
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

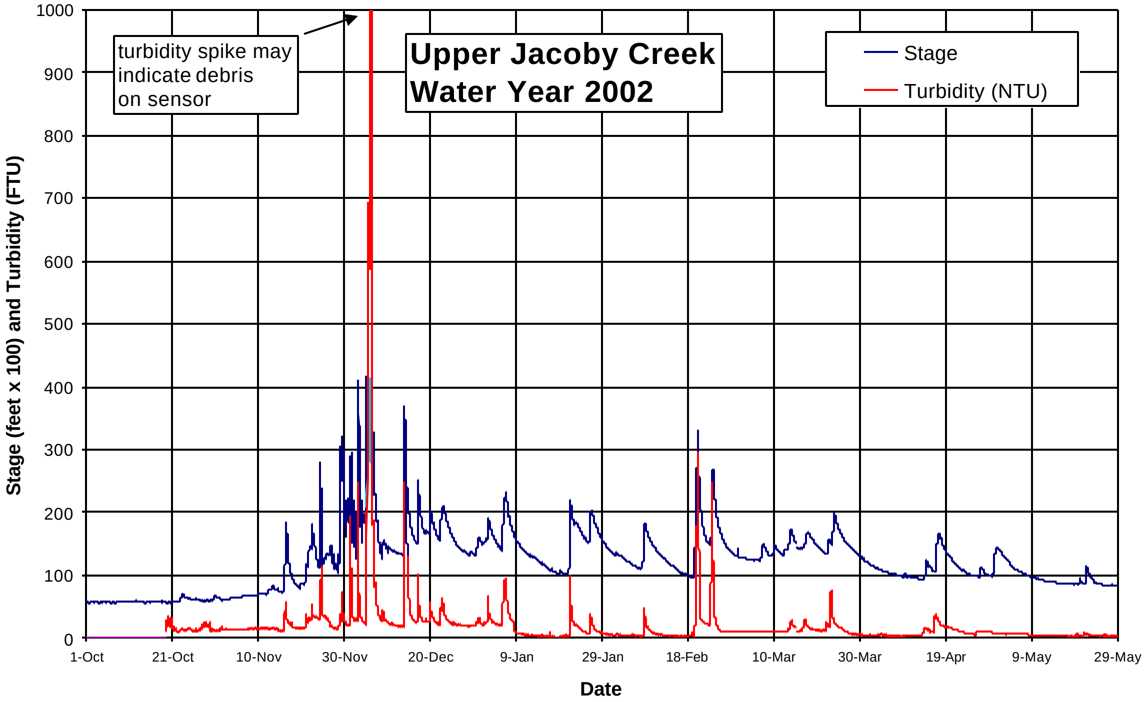

Upper Prairie Creek
Water Year 2002
Stage (feet x 100)
Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

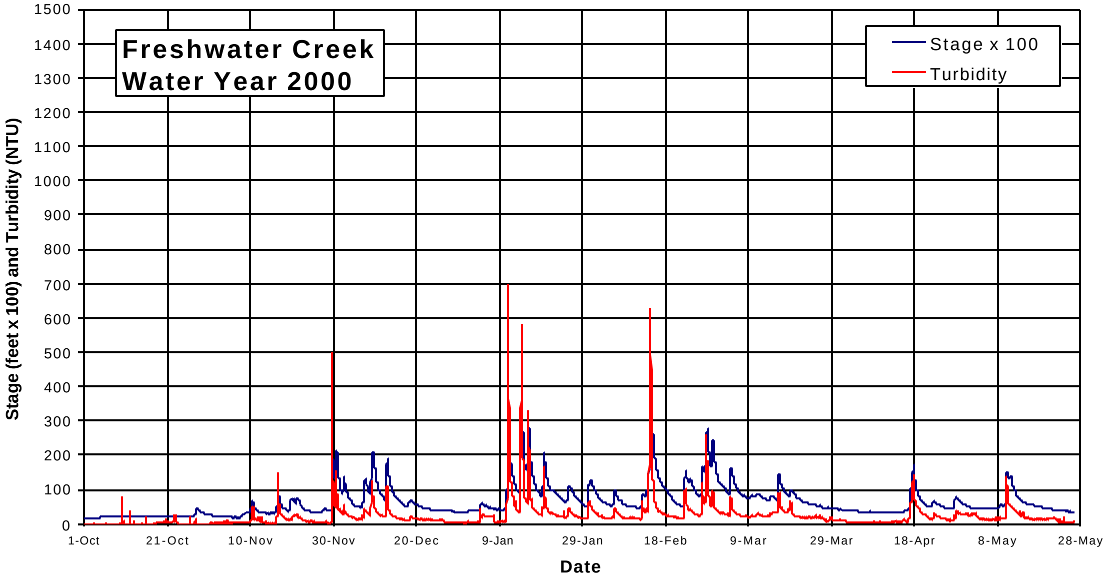

Godwood Creek
Water Year 2000
Stage (feet x 100)
Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
250
225
200
175
150
125
100
75
50
25
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
9-Mar
29-Mar
18-Apr
8-May
28-May
Date

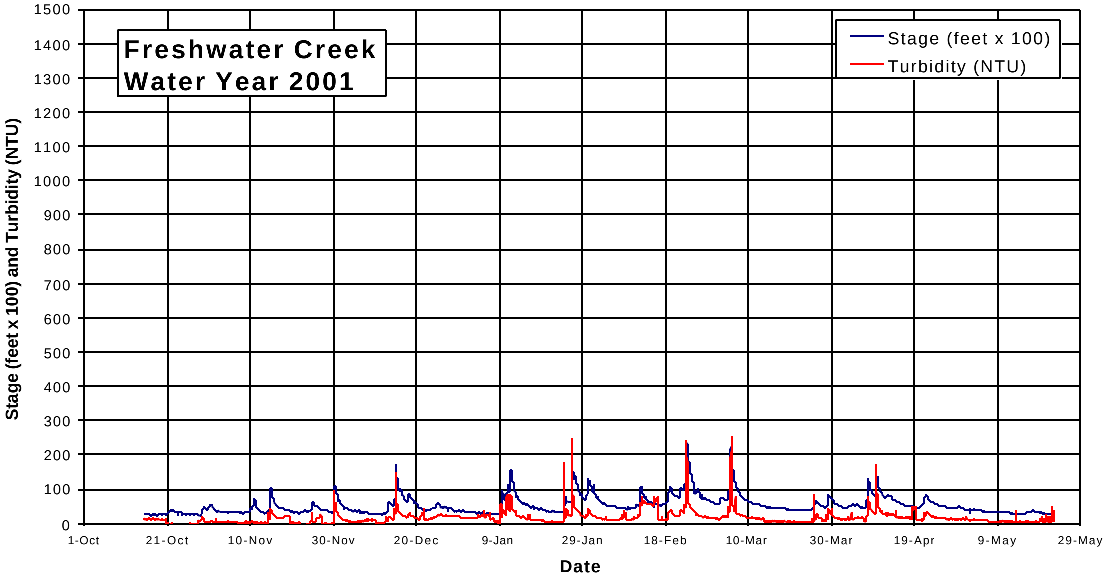

Godwood Creek
Water Year 2001
Turbidity (NTU)
Stage (feet x 100)
Stage (feet x 100) and Turbidity (NTU)
250
225
200
175
150
125
100
75
50
25
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

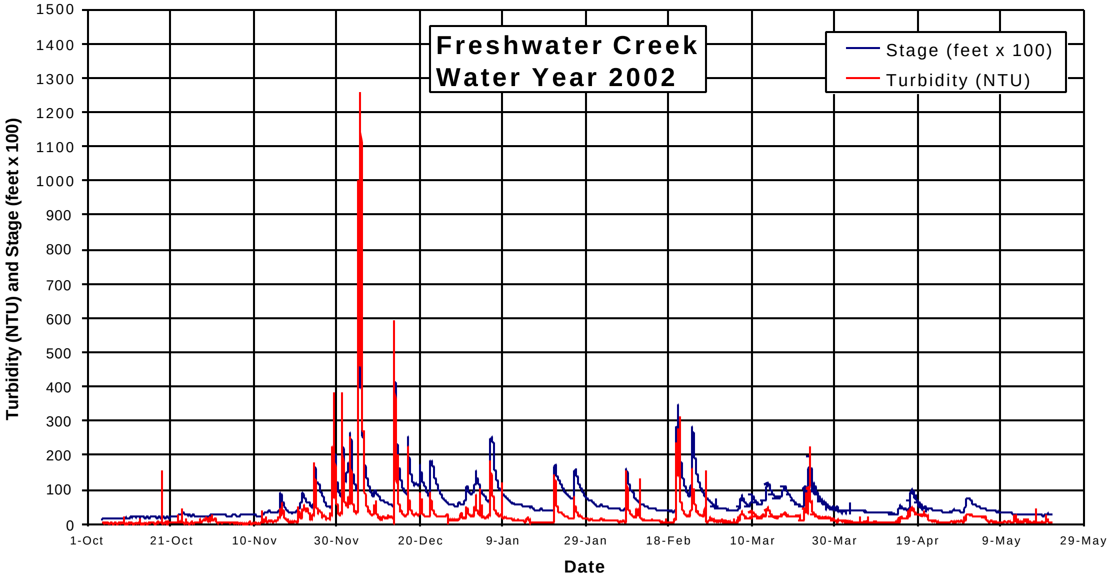

Godwood Creek
Water Year 2002
Stage (feet x 100)
Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
250
225
200
175
150
125
100
75
50
25
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

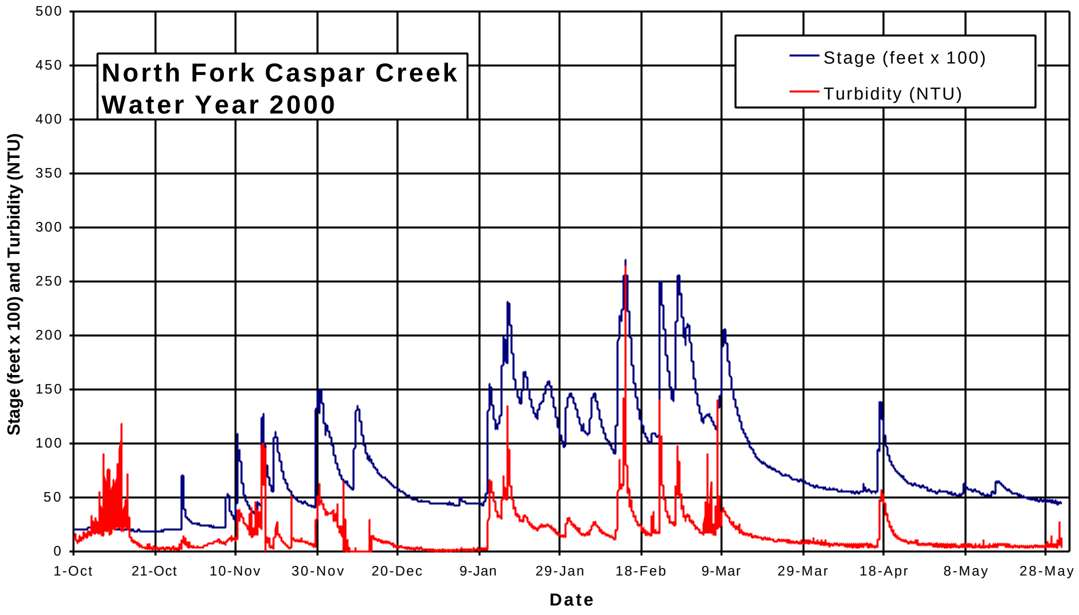

Upper Jacoby Creek
Water Year 2001
Stage (feet x 100)
Turbidity (NTU)
equipment installed 11/20/00
Turbidity (NTU) and Stage (feet x 100)
1000
900
800
700
600
500
400
300
200
100
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

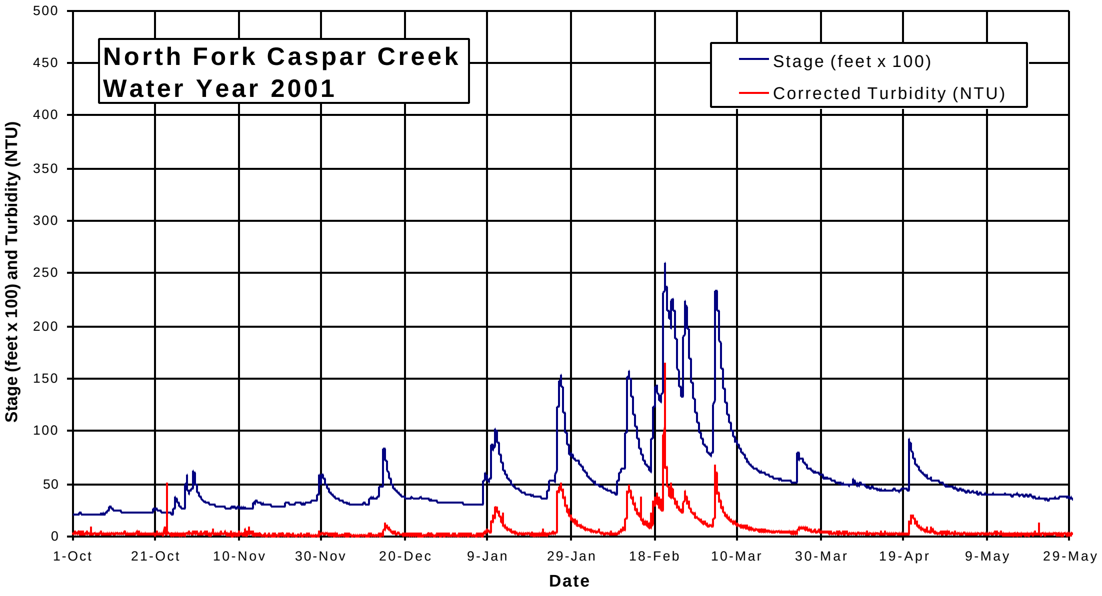

turbidity spike may
indicate debris
on sensor
Upper Jacoby Creek
Water Year 2002
Stage
Turbidity (NTU)
Stage (feet x 100) and Turbidity (FTU)
1000
900
800
700
600
500
400
300
200
100
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

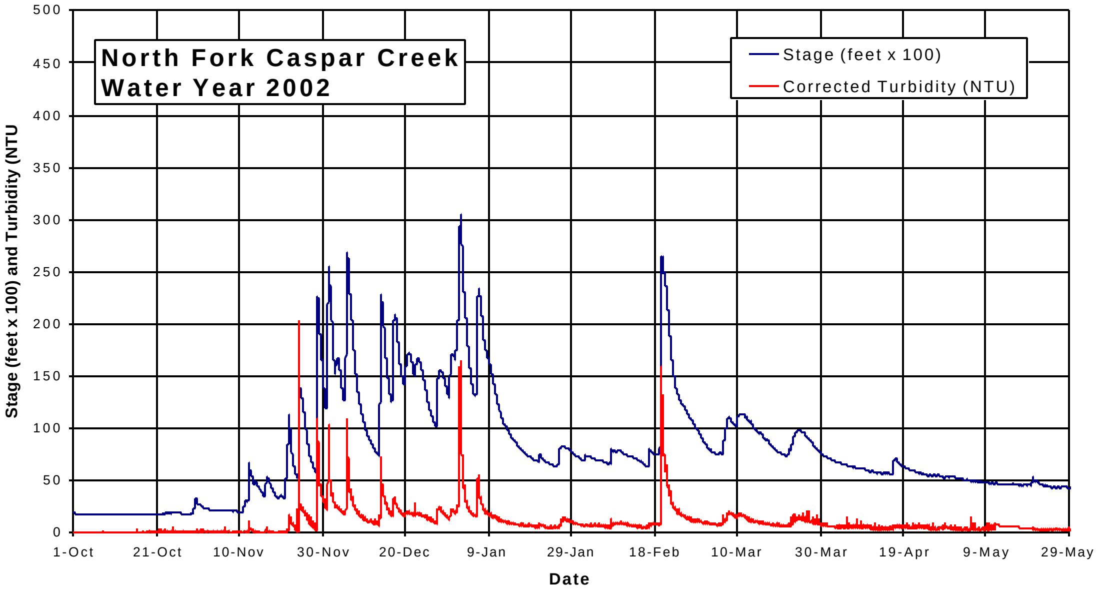

Freshwater Creek
Water Year 2000
Stage x 100
Turbidity
Stage (feet x 100) and Turbidity (NTU)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
9-Mar
29-Mar
18-Apr
8-May
28-May
Date

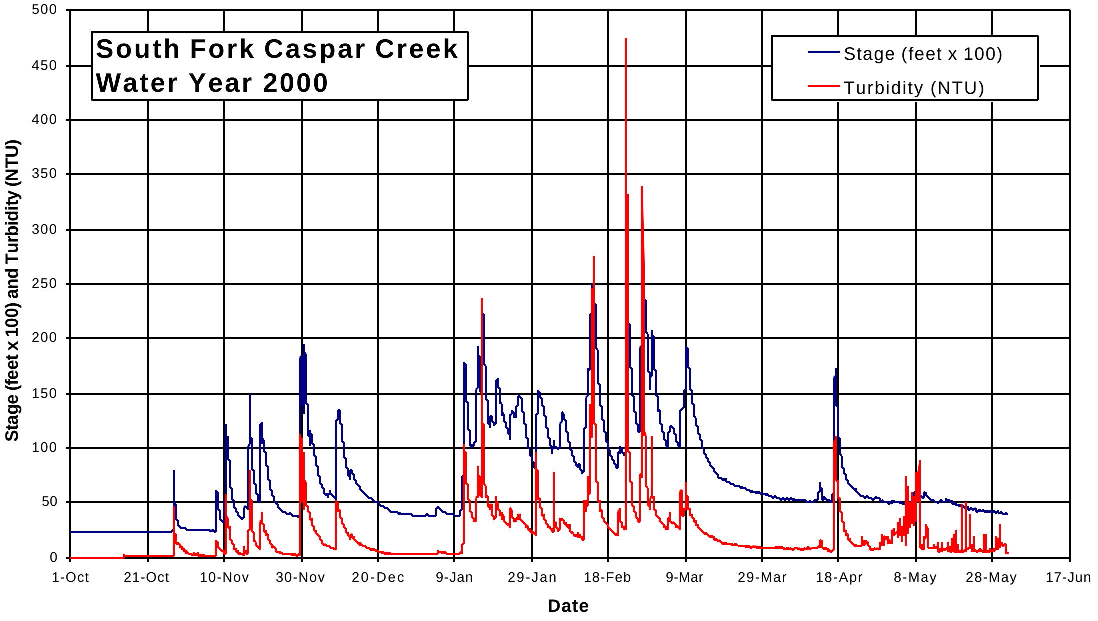

Freshwater Creek
Water Year 2001
Stage (feet x 100)
Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

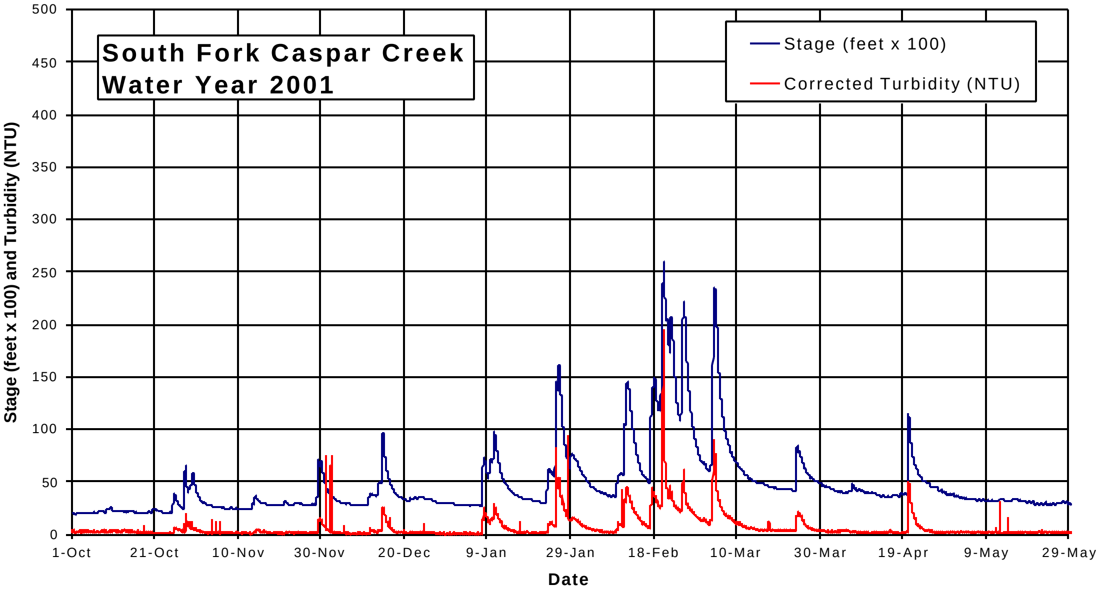

Freshwater Creek
Water Year 2002
Stage (feet x 100)
Turbidity (NTU)
Turbidity (NTU) and Stage (feet x 100)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

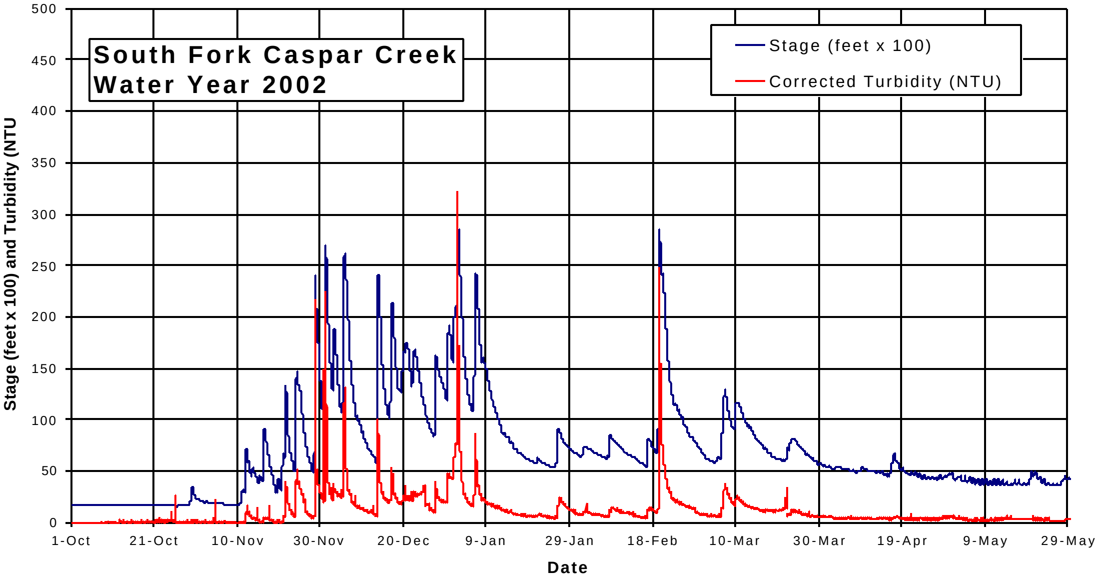

North Fork Caspar Creek
Water Year 2000
Stage (feet x 100)
Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
9-Mar
29-Mar
18-Apr
8-May
28-May
Date


North Fork Caspar Creek
Water Year 2001
Stage (feet x 100)
Corrected Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date


North Fork Caspar Creek
Water Year 2002
Stage (feet x 100)
Corrected Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date


South Fork Caspar Creek
Water Year 2000
Stage (feet x 100)
Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
9-Mar
29-Mar
18-Apr
8-May
28-May
17-Jun
Date


South Fork Caspar Creek
Water Year 2001
Stage (feet x 100)
Corrected Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU)
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date


South Fork Caspar Creek
Water Year 2002
Stage (feet x 100)
Corrected Turbidity (NTU)
Stage (feet x 100) and Turbidity (NTU
500
450
400
350
300
250
200
150
100
50
0
1-Oct
21-Oct
10-Nov
30-Nov
20-Dec
9-Jan
29-Jan
18-Feb
10-Mar
30-Mar
19-Apr
9-May
29-May
Date

APPENDIX C: MULTIPLE REGRESSION OUTPUT

	Y	X1	X2	RESIDUAL OUTPUT			
SITE CODE	**10%NTU**	**Road Density (mi/mi2)**	**Annual Harvest Rate Since 1988 (%)**	*Observation*	*Predicted Y*	*Residuals*	*Standard Residuals*
FTR	49	6.01	4.0%	1	42.97173878	6.028261216	0.97987297
UJC	31	6.37	1.8%	2	33.77235517	-2.772355166	-0.450636725
NFC	20	2.43	3.2%	3	27.68906572	-7.689065722	-1.249830988
SFC	26	5.78	0.0%	4	23.67340155	2.326598452	0.378180516
HOR	20	1.31	0.7%	5	12.63539423	7.364605773	1.197091147
LJO	4	2.67	0.0%	6	13.62075845	-9.62075845	-1.563820947
PRU	11	1.13	0.0%	7	8.640779105	2.359220895	0.383483181
GOD	7	0.00	0.0%	8	4.996506998	2.003493002	0.325660845

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.907140054
R Square	0.822903077
Adjusted R Square	0.752064307
Standard Error	7.279244429
Observations	8

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	2	1231.063003	615.5315014	11.61656371	0.01319859
Residual	5	264.9369973	52.98739945		
Total	7	1496			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	4.996506998	4.406806603	1.13381581	0.308289781	-6.331531498	16.32454549	-6.331531498	16.32454549
X Variable 1	3.234094294	1.240377046	2.607347745	0.047822784	0.0456088	6.422579789	0.0456088	6.422579789
X Variable 2	463.925771	192.3479264	2.411909396	0.060720732	-30.51950672	958.3710488	-30.51950672	958.3710488