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March 17, 2005

Howard Kolb
Central Coast Regional Water Quality Control Board
895 Aerovista Place, Suite 101
San Luis Obispo, CA 93401-7906

Re: THP Monitoring

Dear Howard:

Here is a procedure on how to determine the recommended turbidity for any time after a storm that produces a 1.5-year return period storm (bankfull). The method described below could be used to derive turbidity levels for different return period storms.

Turbidity Recession and THP Monitoring

A study was conducted to estimate long after a storm to monitor a THP for turbidity, and what level of turbidity should be expected. This study is based on the premise that chronic turbidity presents a serious threat to salmon and steelhead and that a timber harvest and the associated roads can be a source of chronic turbidity. The City of Santa Cruz collected 15-minute turbidity data for 165 days from October 30, 2003 through April 15, 2004. The City placed its turbidity sensor in the San Lorenzo near their intake on Tait Street. The USGS San Lorenzo River at Santa Cruz stream gauge (No. 1116100, watershed area = 115 sq-mi) is located just a few feet away from the City's turbidity sensor. Both sets of data are shown in Figure 1.

Trush (2002) identified the following *chronic turbidity thresholds* for anadromous salmonids in streams in Humboldt County.

Table 1. Trush's chronic turbidity thresholds.

Streamflow Condition	Water Discharge Exceedence Probability	Chronic Turbidity Threshold NTU
Mean Daily Discharge	24.00%	10
Winter Base Flow	10.00%	25
Winter Peak Recession	5.00%	70
Winter Peak	2.50%	100

Winter base flow is exceeded only 10% of the time. During winter base flow conditions, the turbidity should be less than 25 NTU. Winter peak streamflow occurs less than 2.5% of the time. The winter peak turbidity should be above 100 NTU only 2.5% of the time. During the recession limb of the hydrograph, the turbidity should exceed 70 NTU only 5% of the time.

Figure 2 shows the turbidity exceedence curve for the City's data for the 2004 water-year. The following City's 2004 turbidity data had the following exceedence probabilities.

- 24% exceedence was 14 NTU
- 10% exceedence was 41.0 NTU
- 5% exceedence was 72.1 NTU
- 2.5% exceedence was 120 NTU

The City's turbidity data exceeded each of Trush's chronic turbidity thresholds. This is not surprising since the San Lorenzo River is listed as impaired for sediment under section 303(d) of the Clean Water Act. Estimates of the time to reach Trush's chronic turbidity thresholds after a storm peak based on the City's data should yield times that are longer than the times expected for a stream in an unimpaired watershed.

The City's turbidity sensor is sampling the discharge from a 115 square-mile watershed which is likely to have a longer sediment and water discharge response and slower recession than the smaller watersheds where timber harvests typically occur. That is, the size of the watershed above the sensor should cause an increase in the time for the turbidity to drop from its maximum to each of the chronic turbidity thresholds.

There are two factors, watershed size and being sediment impaired, working to increase the time for the turbidity to fall from its maximum to each of the chronic turbidity thresholds. Therefore, the estimates of the time required to drop from the maximum turbidity to each of the chronic turbidity thresholds presented in this study should be viewed as upper limits.

Method

Six storms during the 2004 water year were examined to determine the time it takes for the turbidity to decline from its maximum value to each of Trush's chronic turbidity thresholds. Figure 3 shows the maximum turbidity for each storm versus the associated maximum discharge divided by the 1.5-year return period discharge which is an estimate of the bankfull discharge. The 1.5-year discharge for the San Lorenzo River at Santa Cruz gauge was estimated to be 4,200 cfs using the Log Pearson Type III distribution. Table 5 shows the flood frequency data for the USGS gauge, San Lorenzo River at Santa Cruz. Figure 3 shows that the expected turbidity maximum for a 1.5-year (bankfull) discharge of 4200 cfs, is about 448 NTU.

Figure 4 shows the number of hours to reach the 2.5%, 5% and 10% exceedence turbidity thresholds versus the peak water discharge divided by the 1.5-year return period discharge. The power function regressions estimate that, for a bankfull discharge (1.5-year return period) it takes about

- 12 hours to drop from the maximum turbidity to 100 NTU;
- 19 hours to drop from the maximum turbidity to 70 NTU
- 37 hours to drop from the maximum turbidity to 25 NTU

Larger peak water discharges will result in an increase in the time to drop from the maximum turbidity to each of the chronic turbidity thresholds. Smaller peak water discharges should result in a decrease in the time for the turbidity to drop from its maximum to each of the chronic turbidity thresholds.

The small number of storms analyzed and the fact that only data from one station that samples the discharge from an impaired watershed makes the results of this study problematic to apply to other sites

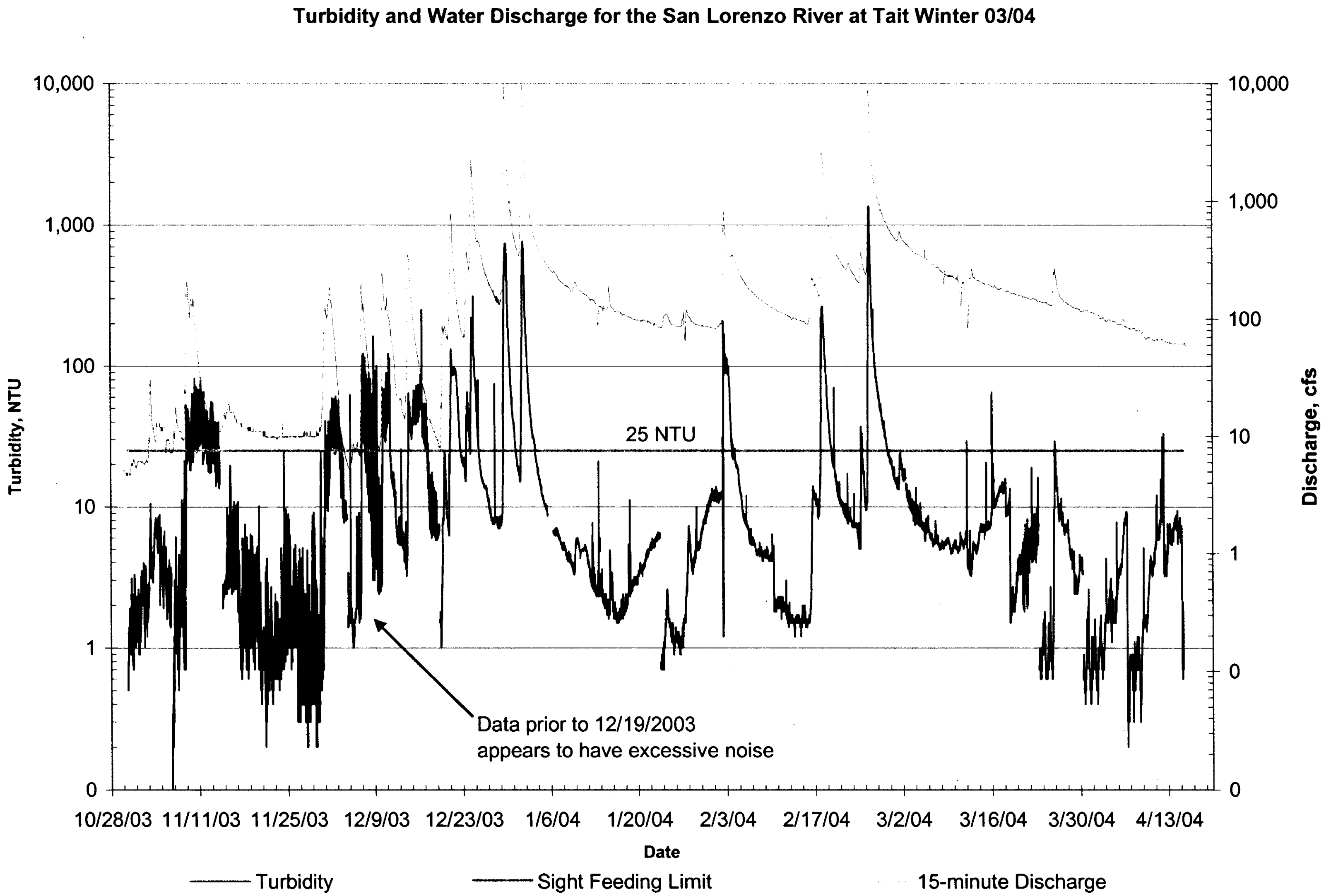

Figure 1. The City of Santa Cruz's 15-minute turbidity data for the 2004 water-year with the USGS 15-minute discharge data from the San Lorenzo River at Santa Cruz stream gauge.

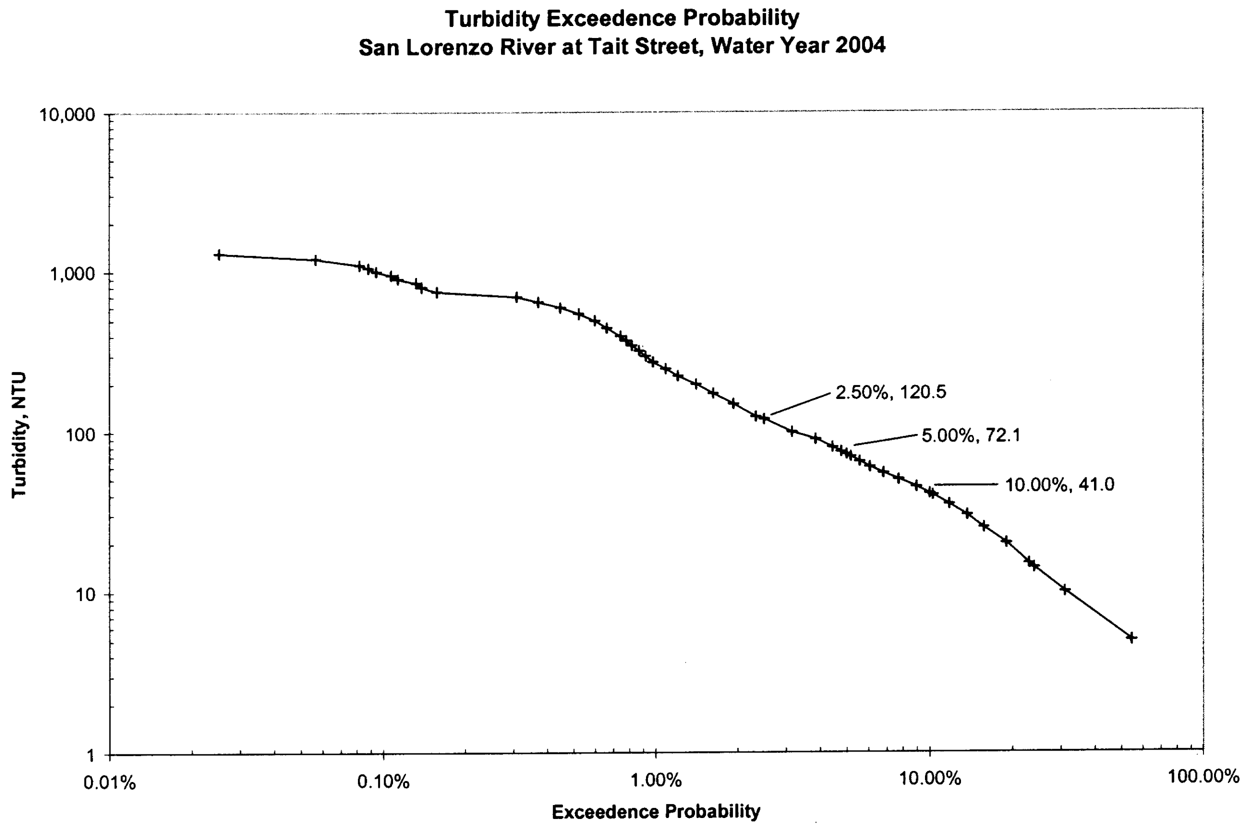

Figure 2. Turbidity exceedence for the City of Santa Cruz's 15-minute turbidity data for water year 2004.

in the Santa Cruz Mountains. However, it does show that a method of analysis can be developed to better predict the time to sample, and it does offer an upper bound on the time to sample.

Estimating the Turbidity Recession

The time used in the regressions starts at the moment that maximum turbidity was recorded by the City's sensor. The first difficulty in applying the regressions to select a reasonable time frame to actually sample a THP is that for a given THP there is no way to know when the maximum turbidity or water discharge occurred.

One approach to this would be to use the Internet to check the rainfall record collected by the Ben Lomond tipping bucket rain gauge operated by the California Department of Forestry near Boulder Creek at an elevation of 2,600 feet. The California Data Exchange Center run by the Department of Water Resources puts the Ben Lomond (BLO) record on line.

An estimate of the time it takes for the turbidity at Tait Street to drop to each of the target turbidity values after the end of each storm can be made by adjusting the times shown in Table 2 by the number of hours between the time of maximum turbidity at Tait Street and the end of the storm at the BLO rain gauge. The BLO rain gauge is located near Boulder Creek which is at the far end of the watershed from the turbidity sensor. Therefore, the time differences calculated in this study between the maximum turbidity and the end of the storm at BLO probably not representative of the time difference for a THP in the upper San Lorenzo watershed. However, the purpose of this study is to propose a method. If this approach is adopted additional data could be analyzed.

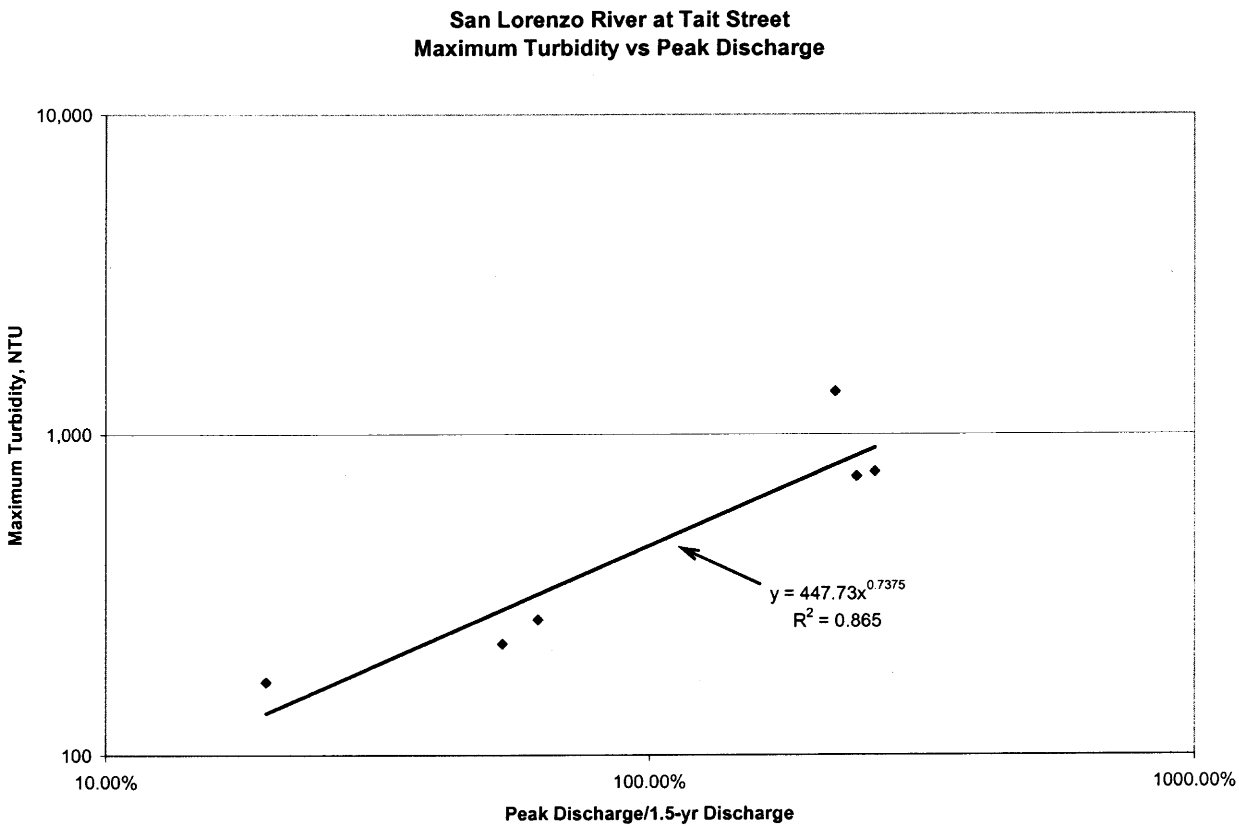

Figure 3. The maximum turbidity verses the associated discharge as a ratio to the 1.5-year return period discharge (bankfull). A power function regression estimates the maximum turbidity associated with a 1.5-year discharge (bankfull) to be about 448 NTU.

The hourly rainfall record of the BLO rain gauge for the 2004 water year was examined to determine when the end of each storm occurred. A graph of the daily rainfall amounts is shown in Figure 10. The end of the storm was defined as the first hour of a 6 hour period with zero rainfall. By this definition, the storm of February 2, 2004 ended 40.8 hours after the maximum turbidity was recorded at Tait Street. The rainfall intensity for most of the time after the occurrence of the maximum turbidity reading at Tait Street was less than 0.1 inch per hour. Therefore, the end of the storm for the February 2 storm was taken to be the time of maximum turbidity.

The time between the end of the storm and the maximum turbidity are shown in Table 3. The time it takes to drop to the target turbidity levels after the end each storm is shown in Table 3 in the *Adjusted Hours* column. Figure 5 shows the regressions for the estimated time it takes to drop to the target turbidity levels after the end each storm. The results for the 1.5-year (bankfull) discharge are virtually the same as estimated in Figure 4.

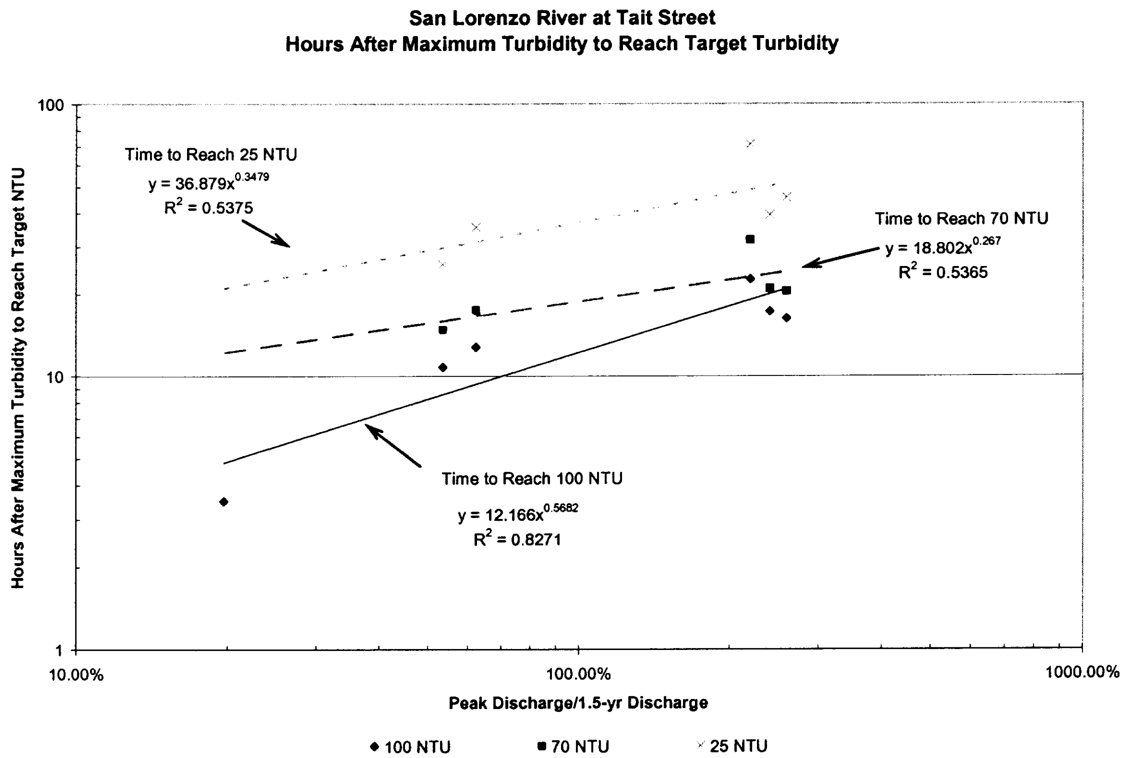

Figure 4. The number of hours after the turbidity peak to reach the target turbidity thresholds for five storms. The 1.5-year return period discharge (4,200 cfs) is an estimate of the bankfull discharge.

Table 2. Data used to create Figure 4 and Figure 5.

Date	Ben Lomond (CDF) Daily Rainfall inches	Maximum Water Discharge	Ratio of Discharge to 1.5-Yr Discharge	Return Period	Maximum Turbidity	Hours to 100 NTU	Hours to 70 NTU	Hours to 25 NTU
12/24/2003	2.48	2,250	53.57%	1.2	221	10.75	14.75	25.75
12/29/2003	4.91	10,100	240.48%	2.72	737	17.25	21	39.25
1/1/2004	3.51	10,900	259.52%	3.5	762	16.25	20.5	45.5
2/2/2004	1.44	827	19.69%		169	3.5		
2/18/2004	2.70	2,620	62.38%	1.25	263	12.75	17.5	35.49
2/25/2004	2.18	9,230	219.76%	2.5	1,355	22.75	31.75	70.99

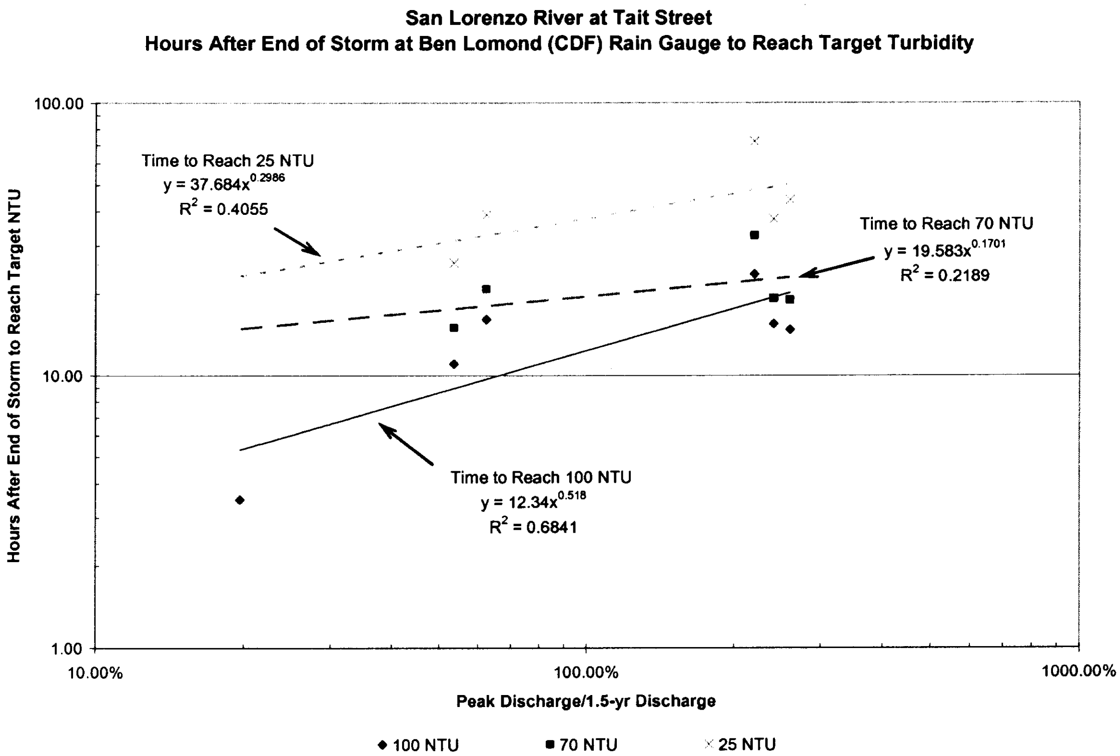

Figure 5. The number of hours after the end of each storm, at the Ben Lomond (CDF) rain gauge, for the City's Tait Street turbidity sensor to reach the target turbidity thresholds for five storms. The 1.5-year return period discharge (4,200 cfs) is an estimate of the bankfull discharge.

Table 3. The time it takes to reach the target turbidity levels was estimated by adjusting the time shown in Table to drop from the maximum turbidity level to the target by the time difference between the maximum turbidity and the end of the storm.

Time of Maximum Turbidity	Time of End of Storm at BLO Rain Gauge	Hours between Max Turbidity and end of storm	Adjusted Hours to 100 NTU	Adjusted Hours to 70 NTU	Adjusted Hours to 25 NTU
12/24/03 12:45	12/24/2003 13:00	0.25	11.00	15.00	26.00
12/29/03 20:45	12/29/2003 19:00	-1.75	15.50	19.25	37.50
1/1/04 16:30	1/1/2004 15:00	-1.50	14.75	19.00	44.00
2/2/04 16:09	2/4/2004 9:00	40.85	3.50		
2/18/04 3:39	2/18/2004 7:00	3.34	16.09	20.84	38.83
2/25/04 15:06	2/25/2004 16:00	0.89	23.64	32.64	71.88

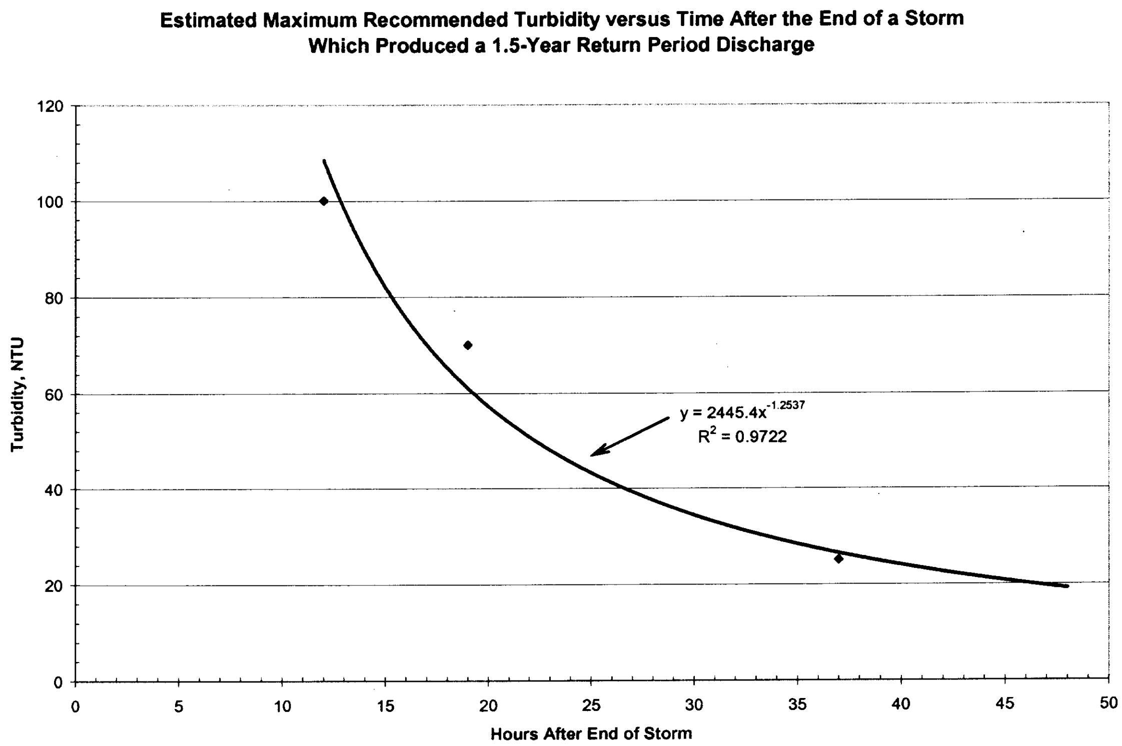

Figure 6. Estimated turbidity recession for a storm that produced a 1.5-year return period discharge. If the turbidity data was from an unimpaired stream it could be used to define the maximum recommended turbidity versus the time after the end of a storm that produced a 1.5-year discharge event. In that case, turbidity readings, for a given time after a storm, that fell above the curve would be undesirably high and readings that fell below the curve would be acceptable.

Figure 6 shows the estimated turbidity recession after a storm that produced a 1.5-year return period discharge (bankfull). If the data that were used to create Figure 6 came from an unimpaired stream, the curve could be used to decide if a given turbidity reading was acceptable or was too high. If a turbidity reading was made a certain number of hours after the storm and the reading fell above the line it would be judged as undesirable. If the reading fell below the line it would be acceptable. Different curves would be required for different return-period storms.

Since the curve in Figure 6 was constructed from data collected on a sediment impaired stream, the curve does not represent the true threshold between acceptable and unacceptable turbidity values. However, any reading that falls above the curve in Figure 6 is clearly not acceptable and would indicate that the watershed above the sensor has a chronic turbidity problem.

Turbidity readings above the curve in Figure 6 would indicate that forensic monitoring was required to determine if the turbidity originated on the THP or was generated elsewhere.

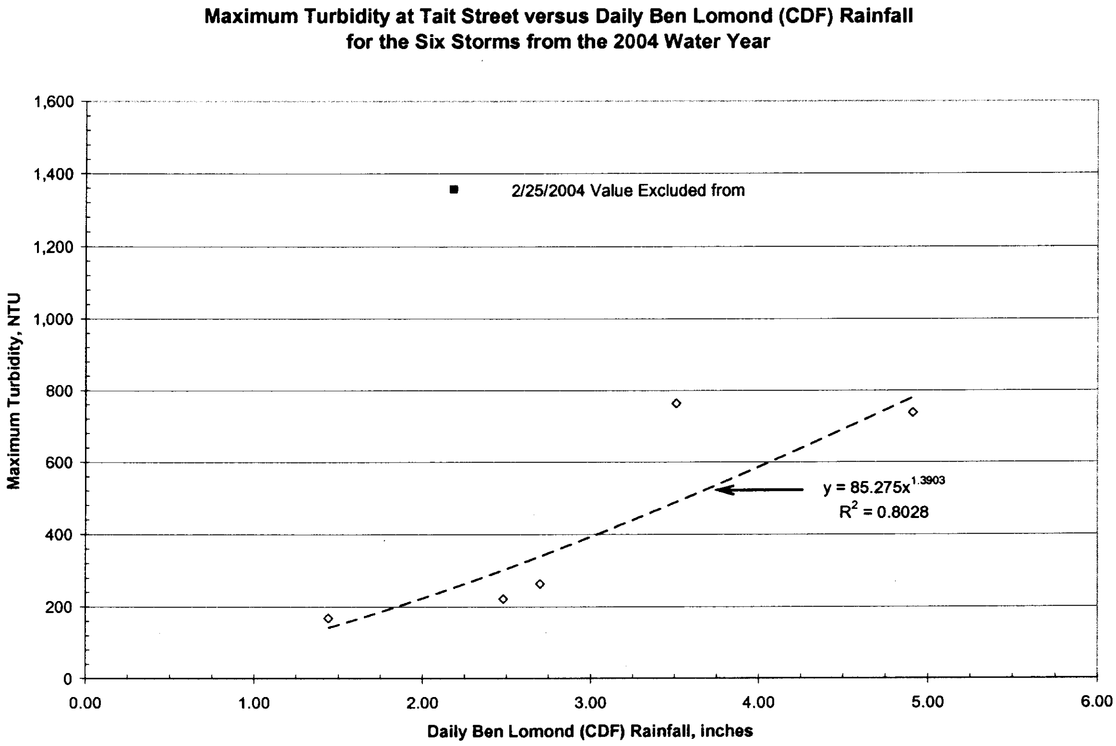

Figure 7. The maximum turbidity at the City of Santa Cruz's Tait Street turbidity sensor versus the daily rainfall recorded by the CDF's Ben Lomond tipping bucket rain gauge (BLO). The maximum turbidity for the 2/25/2004 storm appears to be abnormally high and so was excluded from the regression. The regression developed in Figure 3 estimates that the 1.5-year discharge (bankfull) has a maximum turbidity of about 448 NTU. The regression equation developed in Figure 5 estimates that 3.30" of daily rainfall would be associated with 448 NTU of turbidity at Tait Street.

Figure 7 shows the maximum turbidity at the City of Santa Cruz's Tait Street turbidity sensor versus the daily rainfall recorded by the CDF's Ben Lomond tipping bucket rain gauge (BLO). The maximum turbidity for the 2/25/2004 storm appears to be abnormally high and so was excluded from the regression. The regression developed in Figure 3 estimates that the 1.5-year discharge (bankfull) has a maximum turbidity of about 448 NTU. The regression equation developed in Figure 7 estimates that 3.30" of daily rainfall would be associated with 448 NTU of turbidity at Tait Street. Of course, Figure 7 is based on a small number of samples from a single water year and so may not be readily transferable to other sites. However, the methodology used to create Figure 7 could be applied to a larger data set.

Figure 7 does support the use of 2 inches in 24-hours as a reasonable trigger to monitor THPs after late season storms, if the rainfall is measured at the BLO rain gauge or similar gauge in the Santa Cruz Mountains. The data from the storms used to construct Figure 7 all occurred on or after 12/24/2003.

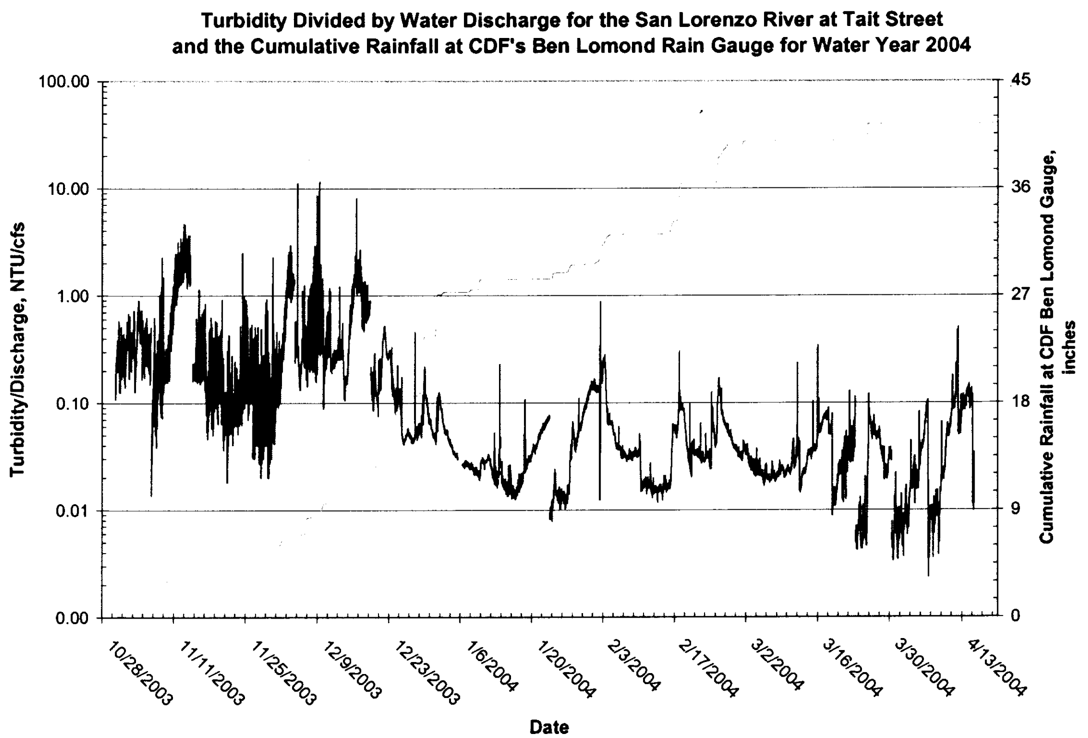

Figure 8. Turbidity divided by water discharge, for the San Lorenzo River near the City's intake at Tait Street, is a measure of the efficiency of fine sediment entering the channel network. Note the drop off in efficiency December 24, 2003, when the cumulative rainfall reaches about 15 inches. The early season turbidity-efficiency shows the need to monitor early storms.

Early Season Storms

Figure 8 shows the turbidity divided by water discharge, for the San Lorenzo River near the City's intake at Tait Street. This ratio is a measure of the efficiency of fine sediment moving through the channel network. Note the drop off in efficiency on December 24, 2003, when the cumulative rainfall reaches about 15 inches. The early season turbidity-efficiency shows the need to monitor early storms. The data in Figure 7 is based on storms after 12/24/2003 so misses the higher efficiency storms that occurred prior to 12/24/2003.

This suggests that the early season recession curves might be different from the later season recession curves. Unfortunately, the early part of the turbidity record appears to have excessive noise in the readings. This noise can be substantially smoothed using a 1-hour moving average on the 15-minute turbidity data. Of course, the presence of the excessive noise raises the questions about the reliability of the early-season readings. Because of these problems, the turbidity recession of the early storms was not analyzed.

Figure 9 compares the turbidity exceedence for the early season and the late season. Early season is defined as October through 12/23/2004, as suggested by Figure 8. Late season is defined as 12/24/2003 through April. Table 4 compares the observed turbidity for water-year 2004 and the early and late season periods of water-year 2004 with Trush's chronic turbidity thresholds. The Tait Street turbidity data is higher than the chronic turbidity thresholds for each of the three time periods considered.

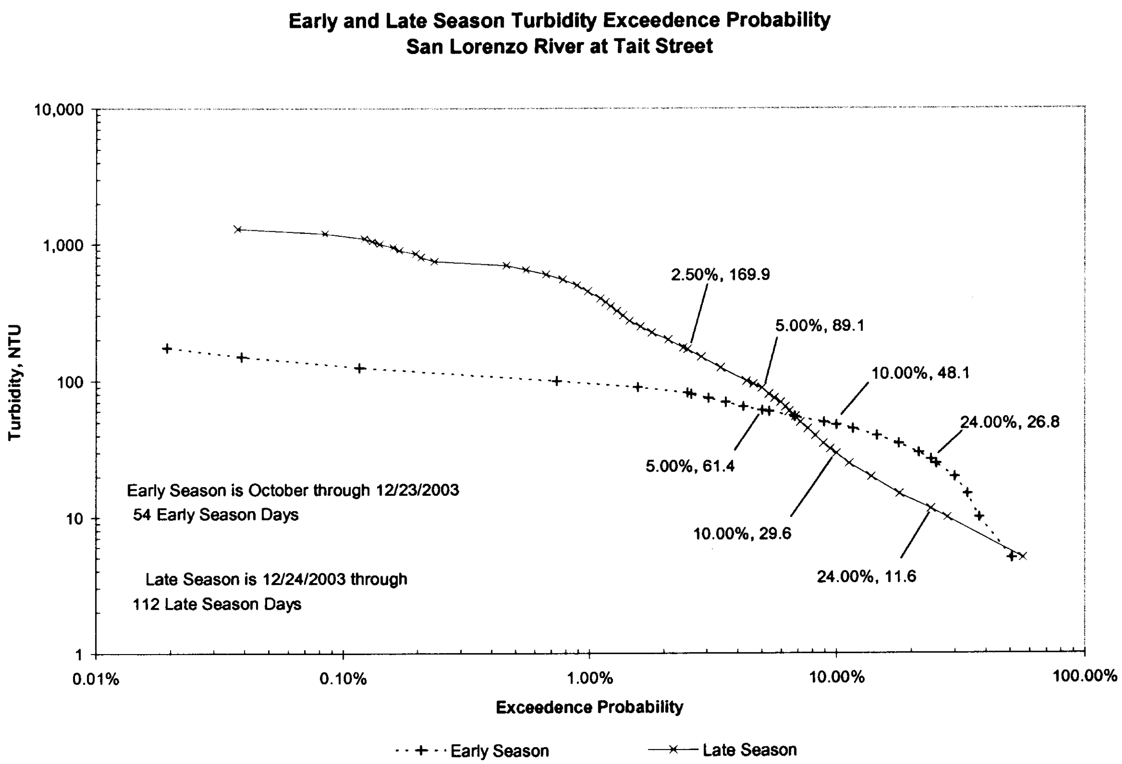

Figure 9. Turbidity exceedence curves for early season and late season. Early season is defined as October through 12/23/2003 and late season is 12/24/2003 through April.

Table 4. Comparison of the turbidity exceedence values for water-year 2004 and the early and late season of water-year 2004 with Trush's chronic turbidity thresholds.

Streamflow Condition	Water Discharge Exceedence Probability	Thrush's Chronic Turbidity Threshold NTU	Water Year 2004 Turbidity with Given Exceedence Probability	Early Season Turbidity with Given Exceedence Probability	Late Season Turbidity with Given Exceedence Probability
Mean Daily Discharge	24.00%	10	14	27	12
Winter Base Flow	10.00%	25	41	48	30
Winter Peak Recession	5.00%	70	72	61	89
Winter Peak	2.50%	100	120	82	170

The early season turbidity is higher for the 24% and 10% exceedence levels than either the late season or the data for the entire winter period. The late season data is only slightly above the chronic thresholds for the 24% and 10% levels. Table 4 shows that early season storms are an important source of low-level chronic turbidity. While early season storms may not move bedload or a large percentage of the total sediment load for the year they do carry elevated levels of suspended sediment relative to the water discharge. The elevated suspended sediment load adversely impacts salmonids. This further underscores the need to monitor early in the season.

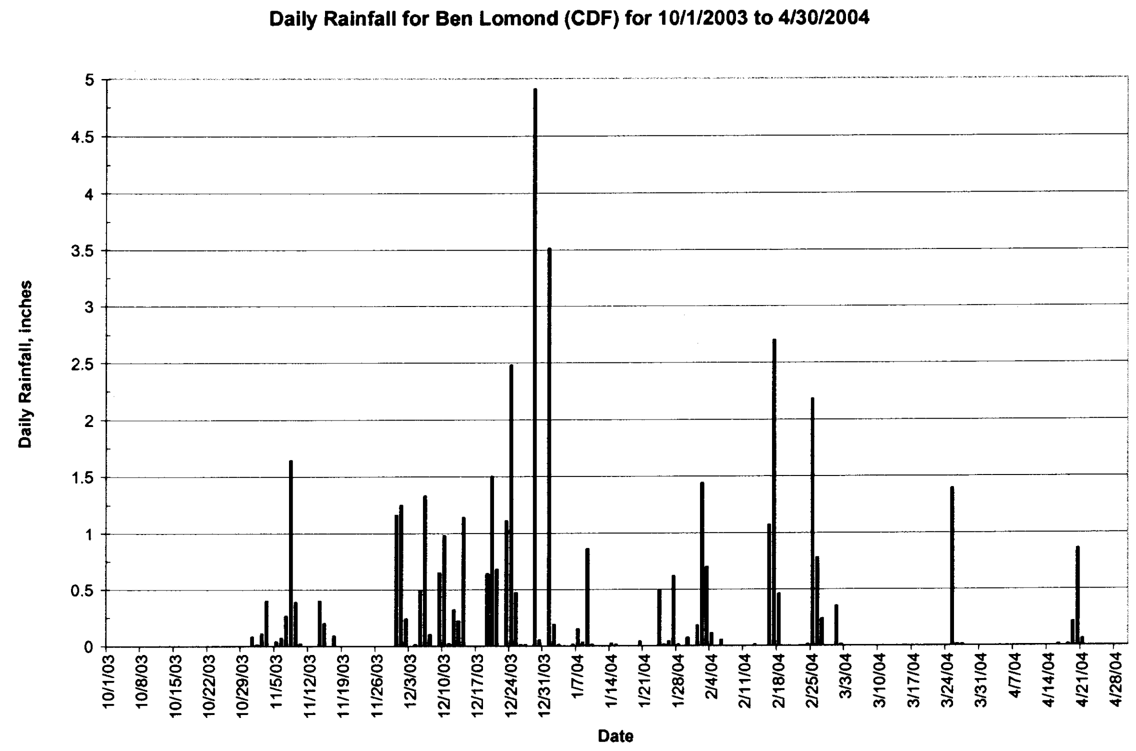

Figure 10. The daily rainfall at the Ben Lomond (CDF) rain gauge, elevation 2,360 feet. The gauge is located near Big Basin. The California Data Exchange Center identifier for this station is BLO.

During the winter of 2004 (165 days), there were 26 days with turbidity greater than 25 NTU. A total of 13.5 of these days occurred during the 54 day period before 12/24/2003 and the remaining 12.5 days with turbidity occurred after 12/24/2003 (112 days). So correcting the chronic turbidity during the early season appears to have a high return on investment.

Figure 10 shows that during the early portion of 2004 water year, prior to 12/24/2003, there were no days with more than 1.64" of rainfall. Figure 1 shows that during the early portion of the 2004 water-year there were six events with turbidity greater than 25 NTU. Figure 10 shows that there were 7 days with rainfall greater than 1 inch and 4 days with rainfall greater than 1.25 inches.

Therefore, storms prior to 12/24 should be monitored if they produce more than 1.25 inches in 24-hours. From 12/24 through the end of the winter monitoring season only storms that produce more than 2 inches of rain in 24 hours should be adequate.

Early season monitoring should be more targeted towards finding sources of fine sediment that are bleeding into the channel system. The monitoring in the later part of the winter might be more focused on identifying failure of erosion control measure or other catastrophic events

Table 5. Flood Frequency for San Lorenzo River at Santa Cruz.

Station: 61000

N = 25, Mean = 8416.04, Std. Dev. = 6872.68

At-site : CV = 0.82, Cs = 1.33, Ck = 4.87
Regional: Cv = 0.87, Cs = 1.17, Ck = 4.14

Log-Pearson III Distribution, MOM Method

Parameter	gamma	alpha	beta
At-Site	10.935014	-0.441400	5.188850
Regional	10.626680	-0.709437	2.963243

Quantile Estimation

T	P	Regional	At-site	Obs.(approx.)	SE
1.20	83.33	1690.92	2235.90	2333.33	865.67
1.50	66.67	3725.79	4212.20	3446.67	1207.65
1.70	58.82	4866.50	5254.95	4798.24	1308.49
2.00	50.00	6337.62	6568.18	7000.00	1391.02
2.50	40.00	8325.92	8314.62	9200.00	1487.71
3.00	33.33	9914.12	9700.89	10966.67	1619.60
3.50	28.57	11226.76	10847.09	11214.29	1805.89
10.00	10.00	19291.47	18071.97	18160.00	5054.11
20.00	5.00	23725.19	22308.82	26980.00	8406.29
50.00	2.00	28550.22	27289.24	NaN	13570.59
100.00	1.00	31497.95	30616.07	NaN	17770.86
200.00	0.50	33920.67	33593.37	NaN	22066.28

Test	Statistic Value	p-value	Decision
Chi-Square	3.48	0.837	Accepted at 95
Klomogorov-Smirnov			

Summary

This preliminary study shows that it is possible to develop a set of curves for different return-period storms that would give a estimate of the acceptable level of turbidity after a storm. Additional data for other turbidity sensors in the Santa Cruz Mountains would refine the values presented in this paper. The important points presented in this paper are that:

- Chronic turbidity is a threat to salmonids
- Turbidity follows well defined recession curves
- Turbidity monitoring for a THP needs to account for the turbidity recession
- The curves in this study are from a stream that has been listed as sediment impaired, so the curve in Figure 6 probably shows higher turbidity values that a similar curve from an unimpaired stream. Direct use of the curve in Figure 6 would probably result in impaired conditions being deemed acceptable.
- Data from relatively unimpaired watersheds could be used to make an improved set of curves estimating the recommended turbidity for any time after a storm. There would be a different curve for different return-period peak water discharges.
- Early season storms have a higher turbidity per unit of water discharge than later season storms
- Early season storms have elevated values for the 24% and 10% turbidity exceedence levels compared to either the late season or the entire winter. Early season (54 days) storms accounted for 13.5 days with turbidity > 25 NTU. Late season (112 days) storms produced 12.5 days with turbidity > 25 NTU.
- Turbidity recession of early season storms may be different than the turbidity recession for later storms
- THPs should be monitored after early season storms that produce more than 1.25" of rain in 24 hours prior to December 24. Early season monitoring should be targeted towards finding sources of fine sediment that bleed into the channel system.
- THPs should be monitored after late season storms (12/24 or later) that produce more than 2" of rain in 24 hours. Late season monitoring should be targeted to finding failed erosion control measures or other catastrophic events.
- The method presented here could be applied to additional 15-minute turbidity data from a variety of creeks to improve the results.

Sincerely,

Dennis Jackson

Dennis Jackson
Hydrologist

References

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