Freshwater Creek, California...

Freshwater Creek Hydrologic Data

STUDY INFORMATION:

- Fisheries Research
- Turbidity Threshold Sampling
- Community Research:
  Salmon Forever

LOCATION / INFORMATION:

- EPA Freshwater Profile

- **Finalized** Fifteen Minute Data:
  Hydroyear 1999
  Hydroyear 2000
- Manual Sample Data:
  Hydroyear 1999
  Hydroyear 2000
- Data Analysis:
  Storm Sediment Load Comparison (1999)
  Storm Sediment Load Comparison (2000)
- Stage and Discharge Relationship:
  Rating Curve
- Cross-section Information:
  PALCO Camp Bridge Cross-section

DATA FORMAT:

- Data Definitions

CONTACT INFORMATION:

- Directory Listing

RELATED INFORMATION AND PUBLICATIONS:

- Redwood Sciences Laboratory Turbidity Publications
- University of California Center for Forestry, Committee on the Scientific Basis for Evaluation of Cumulative Watershed Effects in Forested Landscapes
  - Scientific review of the status of the Freshwater Creek Watershed
  - July 1, 1999 Committee's review of PALCO Report to CDF *An Analysis of Flooding in Elk River and Freshwater Creek Watersheds.*

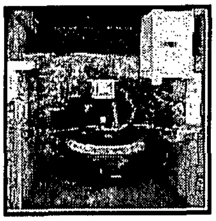
FRESHWATER PHOTO GALLERY

Manual sediment samples and flow measurements are gathered using a crane just down stream of the automatic sampler.

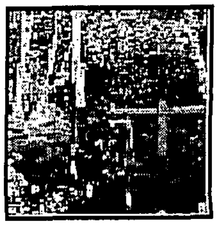
[25KB]

The sediment sampler automatically takes a water sample when storm condition criteria are met.

[121KB]



The boom allows the turbidity probe and water sampler intake to adjust to the dynamic conditions of the stream.



[308KB]

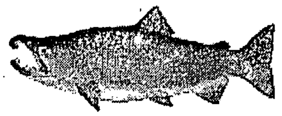
Humboldt County, California

| Turbidity Threshold Publications |
- Salmon Forever - Redwood Community Action Agency - Redwood Sciences Lab -

Freshwater // Last updated on October 19, 2000, by Ben Bray

Freshwater Creek, California...

Annual and Storm Analysis, Turbidity Threshold Sampling (TTS)



Oncorhynchus Kisutch

Click HERE to view a copy of the Salmon Forever **Hydro Year 2000** Highlights document written by project leaders Clark Fenton and Jesse Noell.

OVERVIEW

The Turbidity Threshold Sampling (TTS) program at Upper Freshwater Creek has been successfully maintained for the second hydrologic year with the help of community volunteers. This web page serves as an overview of the data processing sponsored by Redwood Community Action Agency.

The 2000 hydrologic year was a calm year in frequency of storm events, but the magnitude of the storm events that did materialize were of greater significance than those during the 1999 hydrologic year. Three of the six major storms analyzed this year reached peak stages above 4 feet. Two of these storms were back to back in mid January 2000.

This web page also serves as a summary of the various phases of data processing at the Freshwater site. Annual estimates of suspended load based on a linear regression and a LOESS smooth regression are also presented along with six segregated storm load estimates. *Stage discharge data* and *depth integrated sample* data for the Freshwater site are also posted here. Other plots include point samples taken over both hydrologic years, and histogram plots showing consecutive hours of a given turbidity threshold exceedence. You may also download a FORTRAN90 processing routine, turb_thresh_plot, which produces a text file for conversion into a histogram plot in Microsoft EXCEL.

This analysis was carried out on a UNIX based SUN workstation using programs developed by research personnel at the USDA Forest Service Redwood Sciences Laboratory and written in SPLUS, PERL, and FORTRAN. You may email me *[Ben Bray]* if you would like more information on these processing programs. Some of the plots presented on this page were also developed using EXCEL. (If you have read this far you are probably very interested in this information. My advice is to go through this web page and print all the plots before reading the text in this page. And don't forget to read the important note below.

IMPORTANT NOTE: Plots on this web page are presented as *thumbnails*, click on them to view them in **full size**. ALSO, click **BACK** on your web browser to return to this page.

STUDY GOALS

The primary goals of the analysis were to...

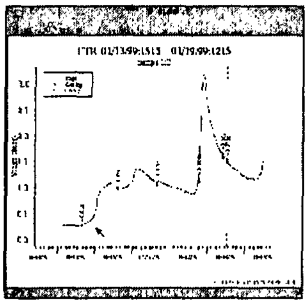
(1) Present annual suspended sediment load estimates for the 2000 hydrologic year at Freshwater Creek.

(2) Identify and predict suspended sediment loads for the six largest storm events in hydrologic year 2000.

(3) Present histogram plots of consecutive exceedence of designated turbidity thresholds [25 NTU, 80 NTU, and 380 NTU].

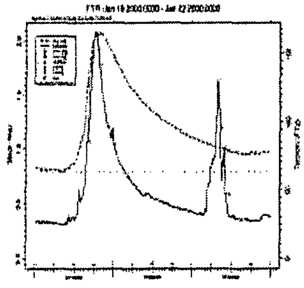
INITIAL PROCESSING

Data processing consisted of a preliminary analysis of the raw data files using a series of data processing routines as mentioned above. The individual raw data files were "appended" into a single file (refered to as the .flo file becasue of the file extension). Some processing programs allow the user to adjust sensor data based on comparisons with field observations. The two plots presented here were taken from two processing programs: **TTS_MAIN_PRO** (left) and **STORMPLOT** (right). The **TTS_MAIN_PRO** figure shows both electronic and observed stage records. Over a five-day period we find that the electronic and observer records begin with close agreement but slowly diverge. Note also that the increased stage during a storm event may also account for a larger difference in observed and electronic records due to wave attenuation, for example.



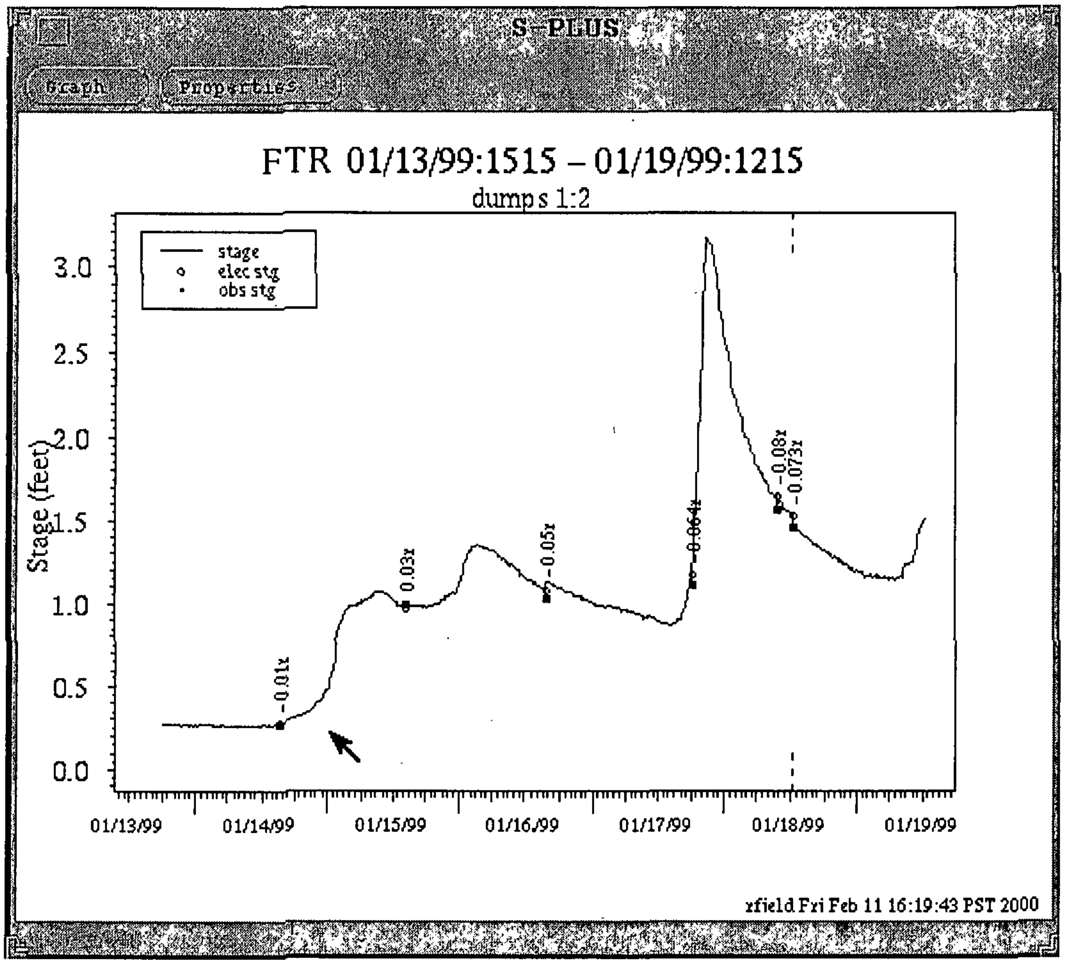
Plot From **TTS_MAIN_PRO** Processing Program

Data analysis began by appending each data dump taken over the course of the 2000 hydrologic year. Appending was completed using a processing program called **TTS_MAIN_PRO** written by R. Field and J. Fisher, employees at Redwood Sciences Laboratory (RSL). **TTS_MAIN_PRO** allows the user to plot the raw stage data and allows the user to adjust the stage data based on observations recorded by personnel in the field.



Raw Plot From **STORMPLOT** Processing Program

A program was also developed by RSL employees in the database language Paradox, which digitizes the field form information and stores the information in a format required by **TTS_MAIN_PRO** for turbidity threshold processing. The next step in the analysis was to construct raw plots of the entire data set. This was completed using a plotting routine written in SPLUS called **STORMPLOT**. **STORMPLOT** has a graphical user interface (GUI), which allows the user to specify subsets of the data by starting and ending date/time of the data record. After entering the record length, the user selects OK and a plot is created with stage and turbidity on the left and right vertical axes, respectively. The abscissa is date and time. After identifying suspect data or gaps in the data set, stage and turbidity data were corrected using two processing programs **TTS_FIX_TURB** and **TTS_FIX_Q**. These two programs prompt the user for the flo filename (e.g. ftr00.flo) along with starting and ending date/time criterion. The user can then select the correction method, such as interpolation or reconstruction from another


S-PLUS
Graph
Properties
FTR 01/13/99:1515 - 01/19/99:1215
dumps 1:2
stage
elec stg
obs stg
Stage (feet)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.01x
0.03x
-0.05x
-0.064x
-0.08x
-0.073x
01/13/99
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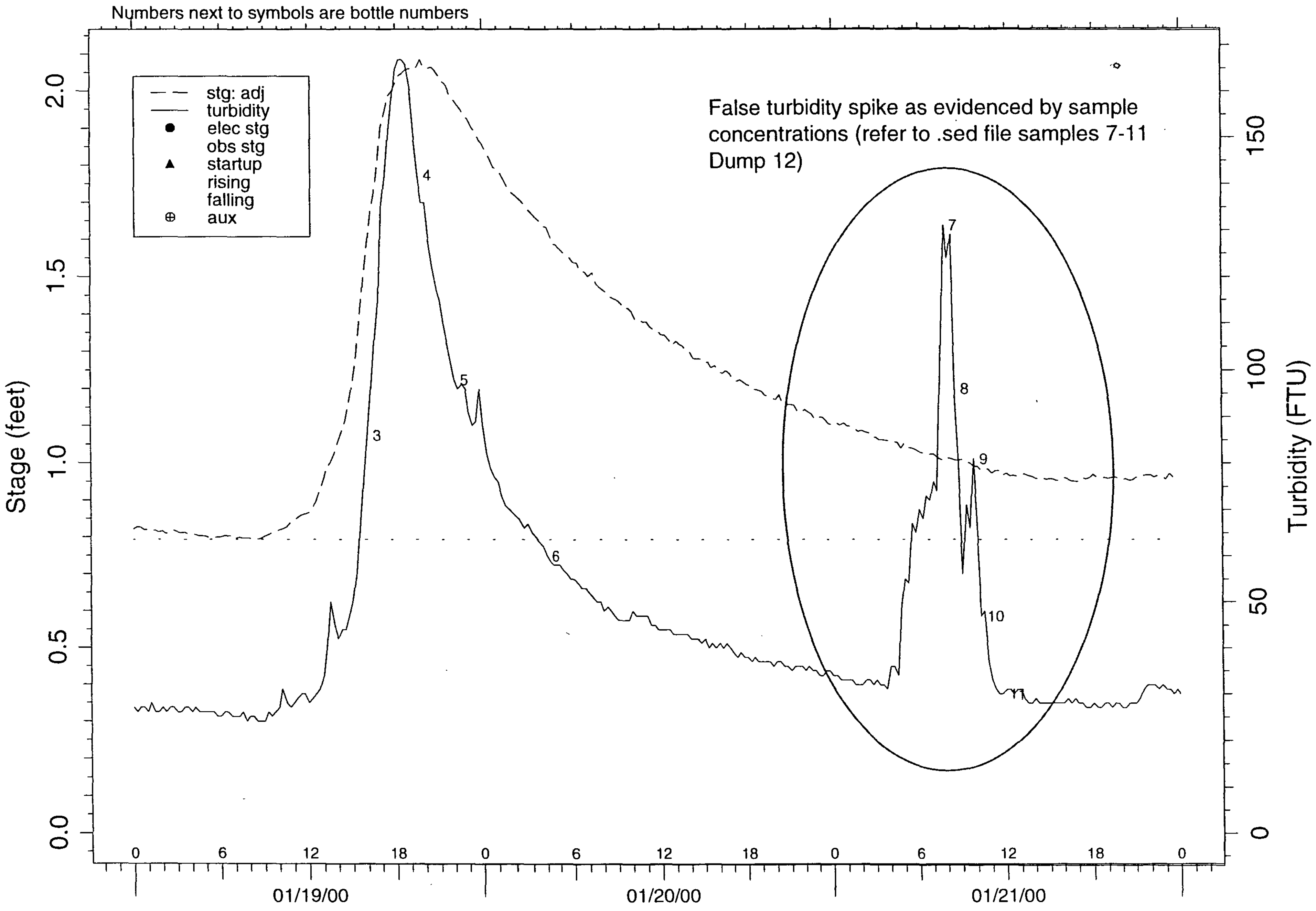


False turbidity spike as evidenced by sample concentrations (refer to .sed file samples 7-11 Dump 12)

bbray Wed Sep 6 12:31:42 PDT 2000

site, if one exists. After correction, the stage or turbidity data is automatically coded according to the method used. Click here to view the stage, turbidity, and lab codes.

THE 2000 HY RATING CURVE UPDATE

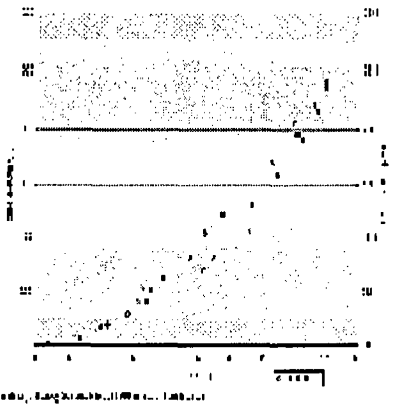
This section presents the stage discharge summary data for the Freshwater station. Fourteen additional measurements were taken during the course of hydrologic year (HY) 2000 as shown below.

1999 Measurements

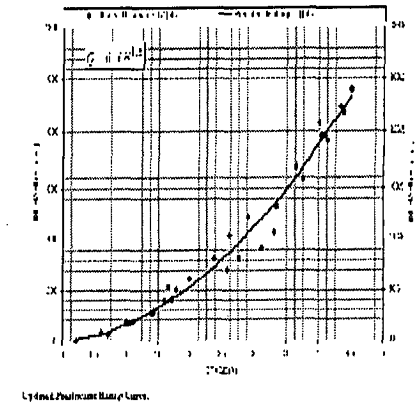
DATE	TIME	QUALITY RATING	AVERAGE STAGE (ft)	DISCHARGE (cfs)
12/17/98	1545	good	0.60	31.4
01/16/99	1635	good	1.05	67.1
01/19/99	1300	fair	1.60	160.2
01/23/99	1116	good	2.37	328.4
01/24/99	1000	good	1.41	109.8
02/06/99	921	poor	1.11	74.3
02/06/99	1009	poor	1.65	215.5
02/06/99	1054	poor	2.61	413.00
02/06/99	1150	poor	3.65	674.9
02/06/99	1306	fair	4.00	831.0
02/06/99	1524	good	3.30	423.7
02/06/99	1602	good	3.10	363.2
02/06/99	1701	fair	2.75	325.9
02/06/99	1758	fair	2.58	285.3
02/08/99	1556	good	1.42	116.5
02/15/99	905	good	1.005	68.6

2000 Measurements

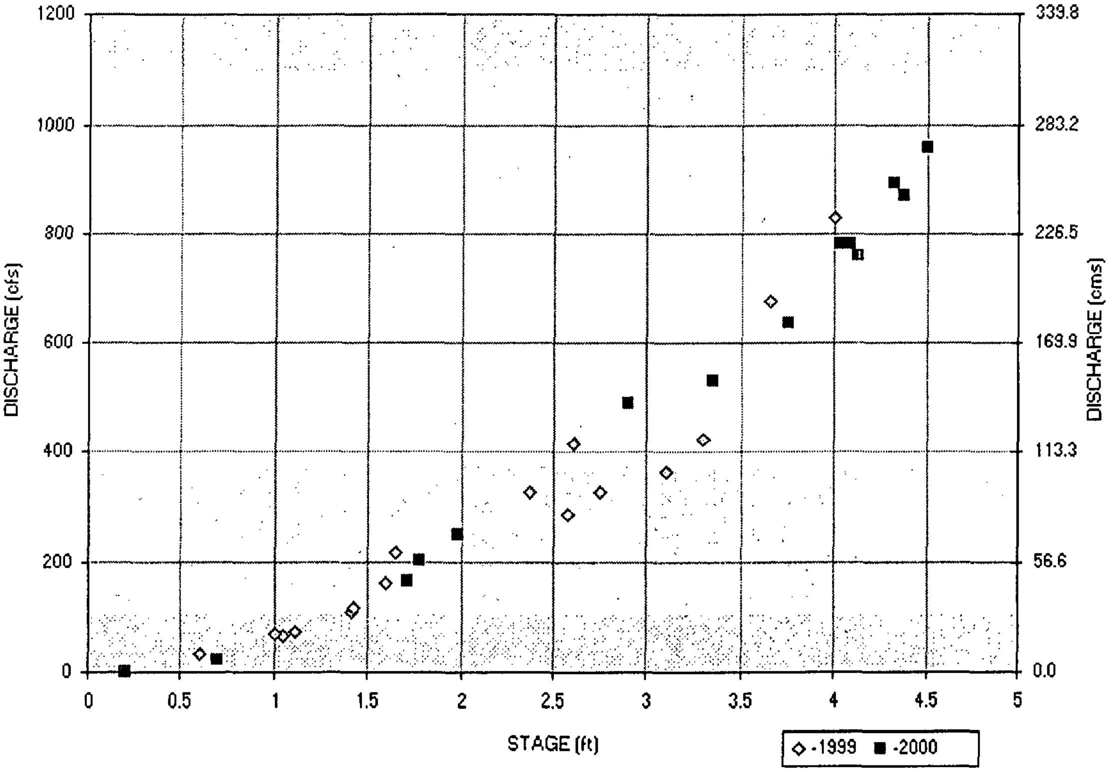
DATE	TIME	QUALITY RATING	AVERAGE STAGE (ft)	DISCHARGE (cfs)
11/05/99	1700	fair	0.21	0.4
11/21/99	1450	fair	0.702	21.8
01/11/00	2113	good	1.78	203.3
01/11/00	1740	good	1.98	250.1
01/14/00	1112	good	4.325	891.9
01/14/00	1031	good	4.5	958.5
01/14/00	1627	good	2.90	488.3
01/14/00	1235	good	4.025	782.9
02/14/00	1157	good	4.08	781.3
02/14/00	1252	good	4.38	869.2
02/14/00	1429	good	4.13	760.8
02/14/00	1706	good	3.75	634.9
02/14/00	1813	good	3.35	528.8
02/28/00	2046	good	1.71	163.5



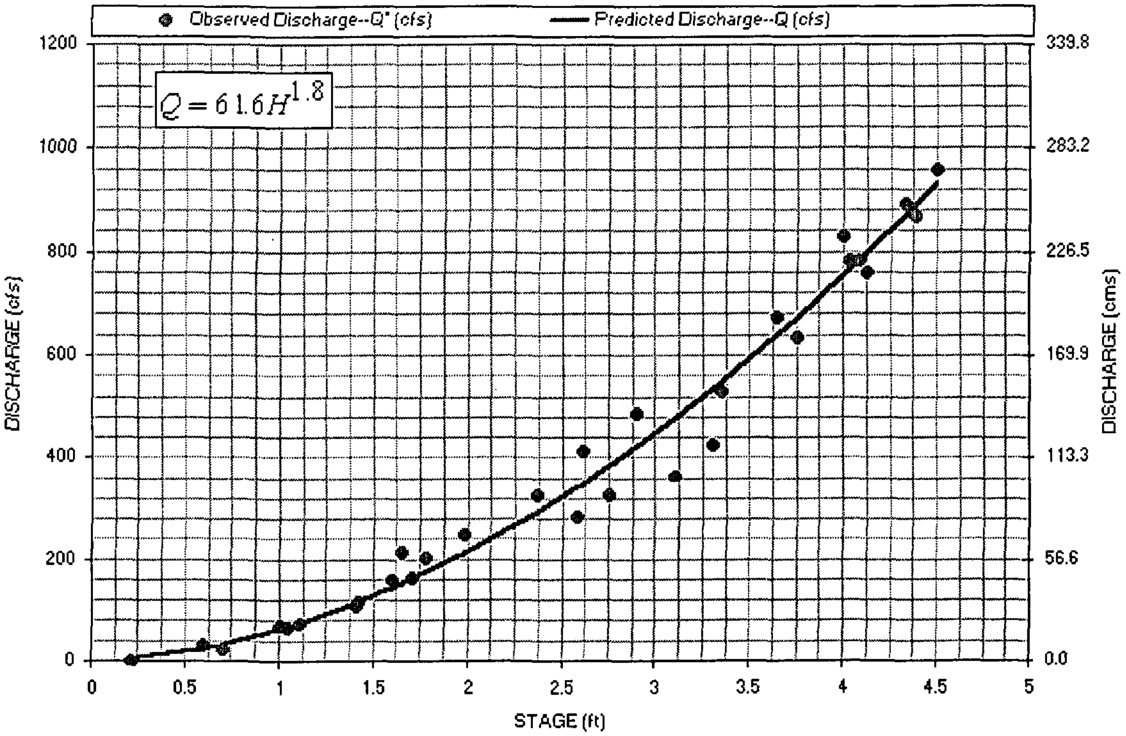
This first plot shows both 1999 and 2000 HY measurements in one figure. There were concerns that the stage/discharge rating relationship was changing due to deposition at the study site. From this plot no drastic changes in the rating relationship were shown as was expected given the amount of deposition (~ 1 ft) at the study site. Clearly there is more variance, and thus more uncertainty, in the rating relationship as discharge increases.



This next plot shows the rating curve fit to the complete data set. This fit was carried out using the solver package in MS Excel. The objective was to minimize the sum-of-the-square-residual between observed and predicted data assuming a power relationship between stage (*H*-feet) and discharge (*Q*-cubic feet per second). When the 1999 HY rating equation [$Q=68.3H^{1.68}$] is compared with the combined 1999-2000 HY rating equation [$Q=61.6H^{1.81}$] a slight decrease in the intercept is noted. Also the exponent of the power function has increased slightly. For hydrologic year 2000 the magnitude of events captured were greater than that in 1999, thus the rating equation has changed slightly due to the additional measurements.



Discharge Rating Scatter Plot of 1999 & 2000, Freshwater.



Updated Freshwater Rating Curve.

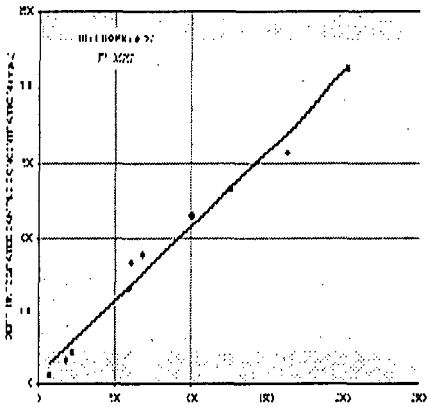
DEPTH INTEGRATED SAMPLING (DIS) ANALYSIS

This year ten measurements were taken by Salmon Forever field personnel. The samples were analyzed at the Sunny Brae Suspended Sediment Laboratory for suspended sediment concentration. The final concentrations along with corresponding point sample concentrations (taken by the ISCO sampler) are presented in tabular form.

DIS DATA

DATE	TIME	DIS CONC. (mg/L)	LAB CODE	PS CONC. (mg/L)
01/11/00	1945	2.162E+02	0	2.193E+02
01/11/00	2145	1.636E+02	0	1.794E+02
01/14/00	1015	1.577E+03	0	1.626E+03
01/14/00	1100	1.335E+03	0	1.261E+03
01/14/00	1615	6.571E+02	4	5.945E+02
02/14/00	1245	2.117E+03	0	2.024E+03
02/14/00	1500	1.162E+03	0	1.007E+03
02/14/00	1700	8.845E+02	0	6.816E+02
02/14/00	1745	8.263E+02	0	6.058E+02
02/28/00	2030	5.900E+01	0	7.163E+01

The plot shown here is the linear regression fit to the 2000 DIS data set using EXCEL. From the slope of this regression (1.01) one can infer nice agreement with point samples taken by the ISCO and depth integrated samples taken by field personnel. The variance from this linear regression model is likely attributed to the level of precision in the laboratory work.

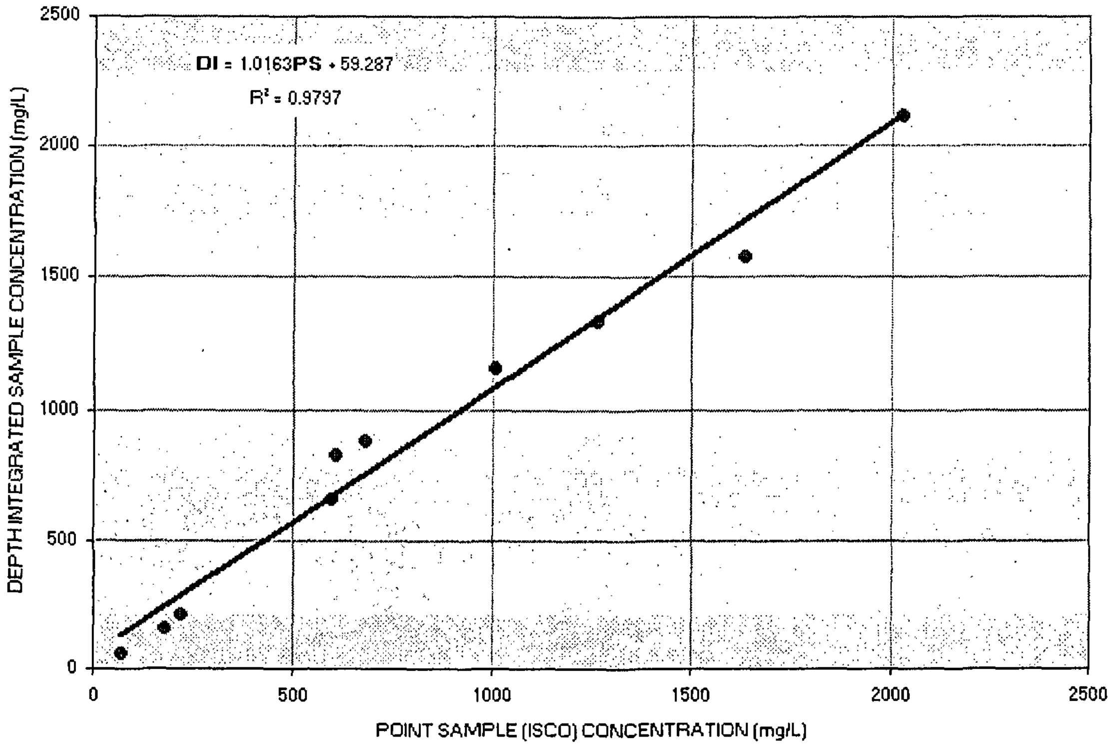


DIS Linear Regression

A paired f-test was used to test whether we could reject the model **DI = PS**; a linear model with slope of one and intercept of zero (Note: **DI** - Depth Integrated and **PS** - Point Sample). The outcome of the test was that we *could not* reject the **DI = PS** model. What this boils down to is that the annual load predicted from point samples *were not* adjusted for the entire cross section. More DIS data will narrow the range in confidence of both the slope and the intercept. Perhaps next year ISCO concentrations may heve to be adjusted to account for a greater sediment concentration across the whole cross section due to more confidence in the intercept of the linear regression model.

ANNUAL LOAD ESTIMATION

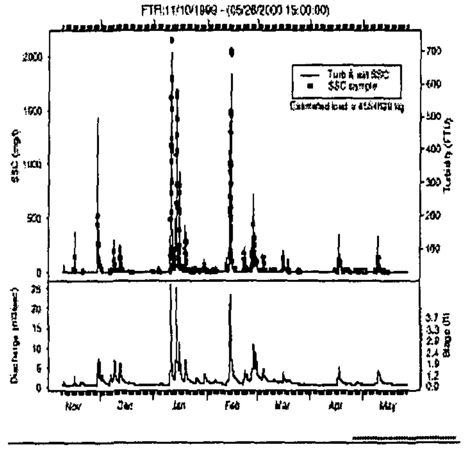
The next part of the processing procedure is the most exiting part and so it is my favorite; determination of the annual load and storm loads for Freshwater Hydrologic Year 2000. The loads are presented first in graphical



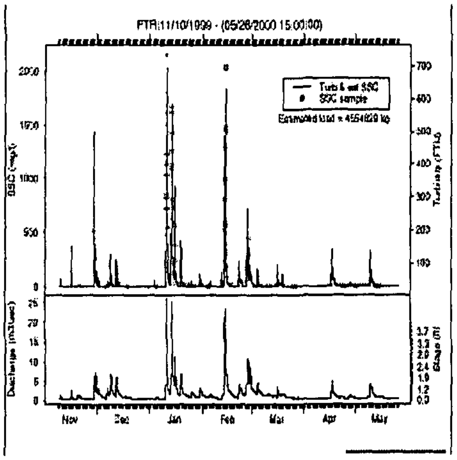
Depth Integrated Sample vs. Pumped Sample, FTR 2000.

form, followed by model fits to the ftr00.sed data set. Then the loads using both the linear model and LOESS smooth model are presented in tabular form.

Annual Load With Bottle Numbers



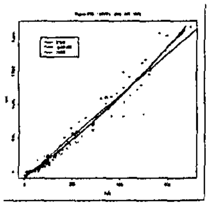
Annual Load Without Bottle Numbers



Annual Load With Bottle Numbers

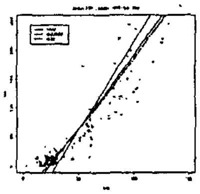
This first plot shows the complete data set for hydrologic year 2000. Sample bottles show up as solid dots on the sedigraph. On the sedigraph the left scale is suspended sediment concentration (mg/L) and the right scale is turbidity (NTU). The bottom section of the plot is the hydrograph where the left scale is discharge (m^3/s) and the right scale is stage (ft). The load presented on this graph is based on the linear regression model shown below.

Here we have the same plot as that on the left, only the sample bottles are actual sample bottle numbers within a given dump (refer to codes page).



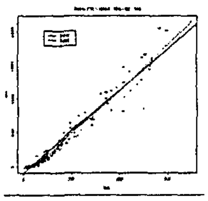
Linear, Polynomial, and Cubic Fits to Data Set
Scale: 0-2200mg/L, 0-700NTU

The plot above shows the linear regression model along with the quadratic and cubic polynomial fits to the 2000 data set. You'll note that the cubic and quadratic fits plot virtually on top of each other. Though they fit slightly better on the lower end, they tend to overestimate the peak concentrations, and thusly are less desirable as compared with the linear model.



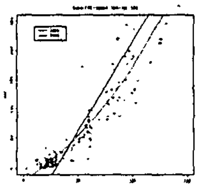
Linear, Polynomial, and Cubic Fits to Data Set
Scale: 0-250mg/L, 0-150NTU

Here we show the linear, quadratic, and cubic fits on a finer scale (Turbidity Range:0-150 NTU, Suspended Sediment Range:0-250 mg/L).



Linear and LOESS Fits to Data Set
Scale: 0-2200mg/L, 0-700NTU

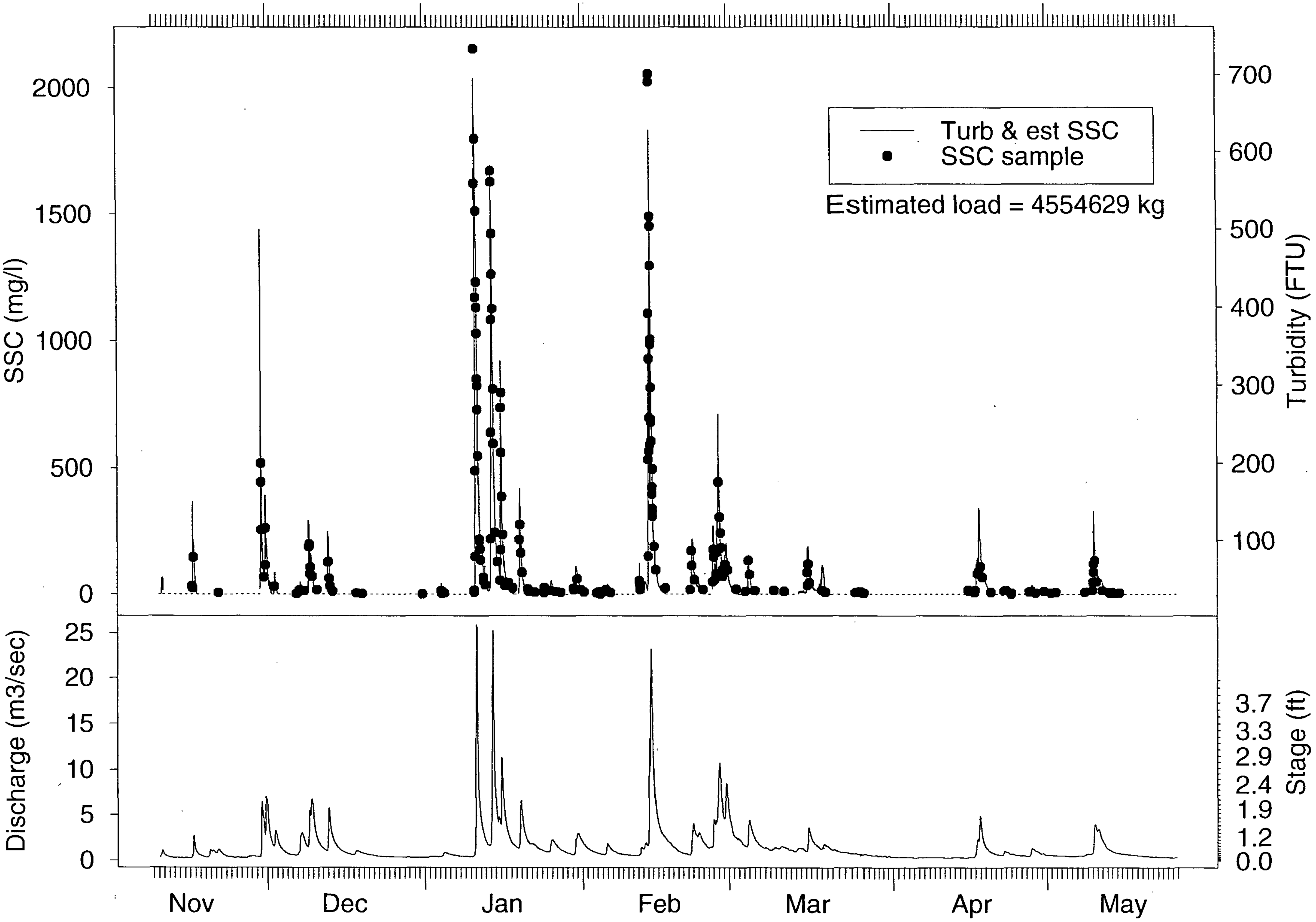
This plot shows both the linear and LOESS smooth models. Just as we found last year, the LOESS smooth model is superior at fitting the high end of the turbidity-suspended sediment relationship. The linear model slightly under predicts the peak samples.



Linear and LOESS Fits to Data Set
Scale: 0-250mg/L, 0-150NTU

Above we show the linear model against the LOESS smooth model on a finer scale. Again the LOESS model tends to follow the general trend of the data more closely than the linear model at this range. Though there is a lot of scatter in the data at this scale, one can make out a definite curve-like trend in the data set. (Turbidity Range:0-150, Suspended Sediment Range:0-250)

FTR:11/10/1999 - (05/26/2000 15:00:00)



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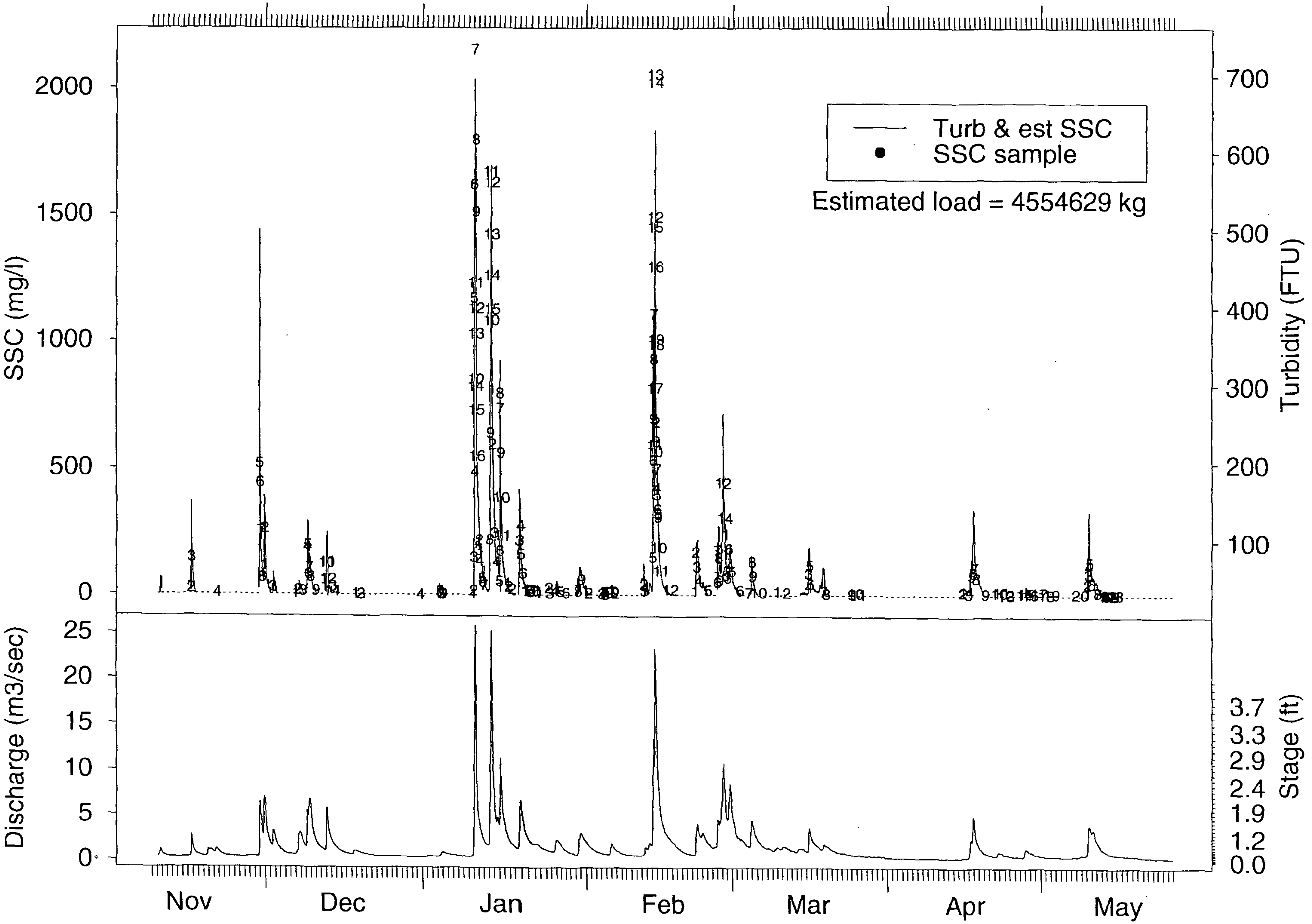
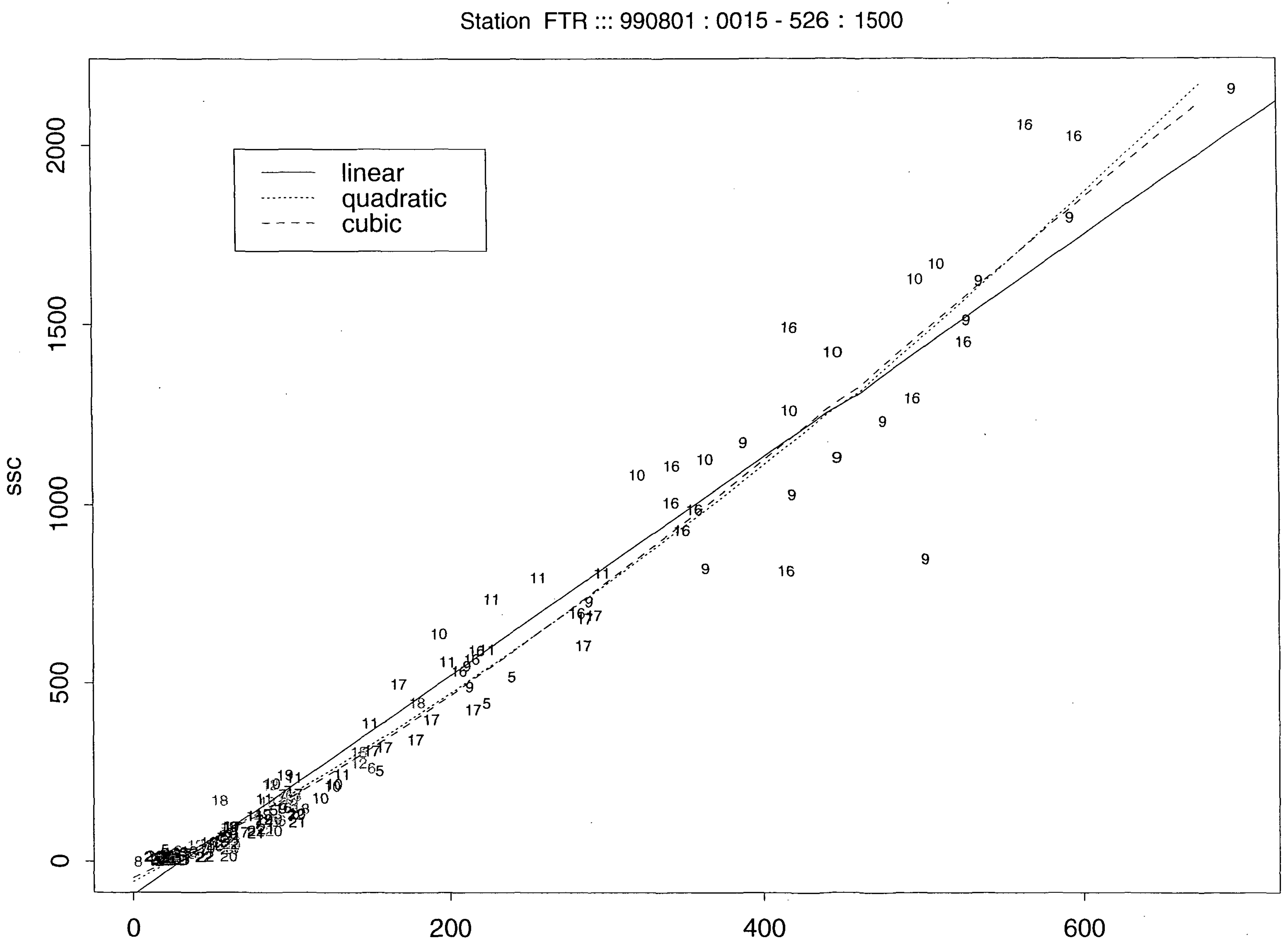
FTR:11/10/1999 - (05/26/2000 15:00:00)




Station FTR ::: 990801 : 0015 - 526 : 1500
linear
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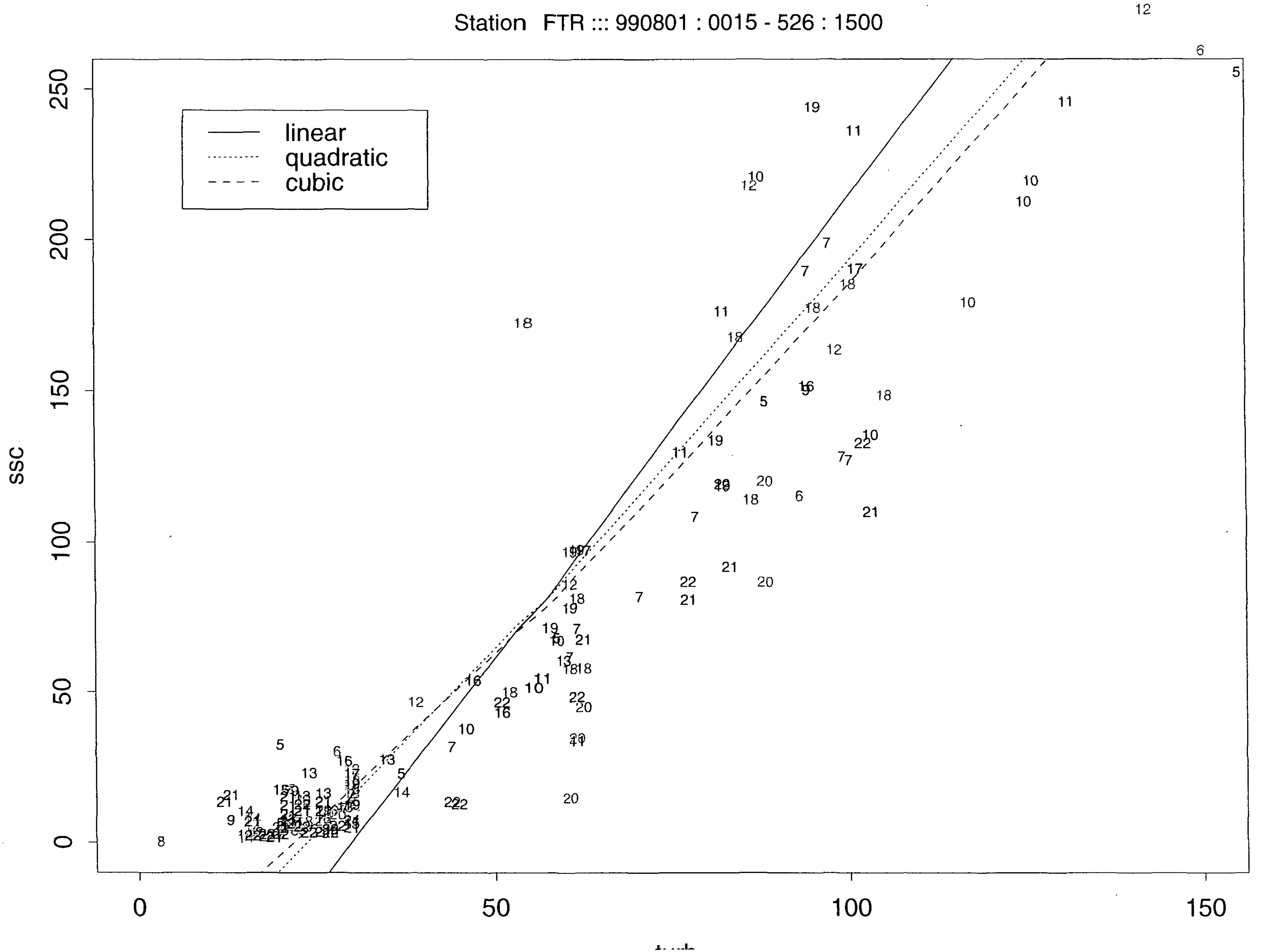
400
600


Station FTR ::: 990801 : 0015 - 526 : 1500
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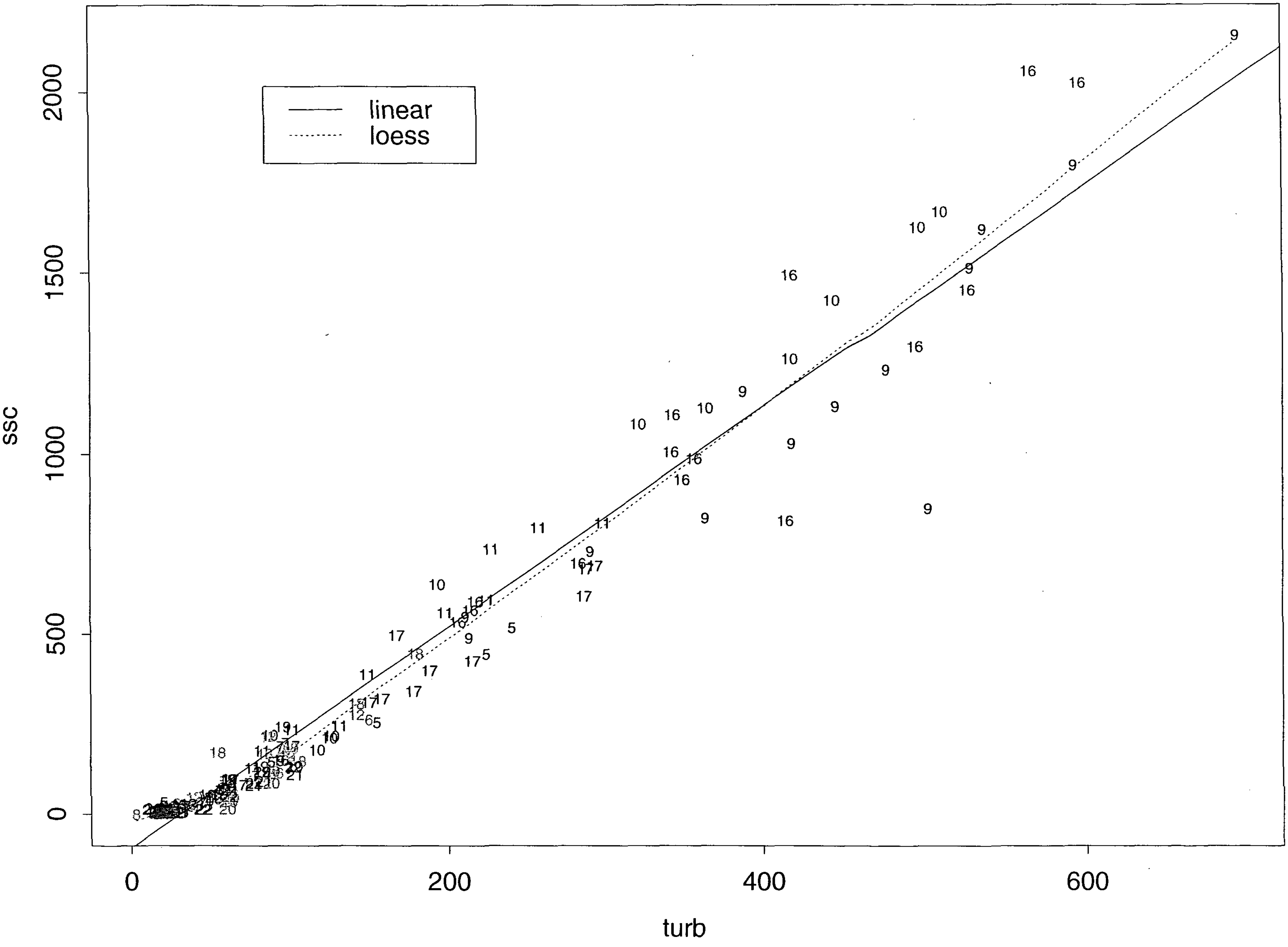

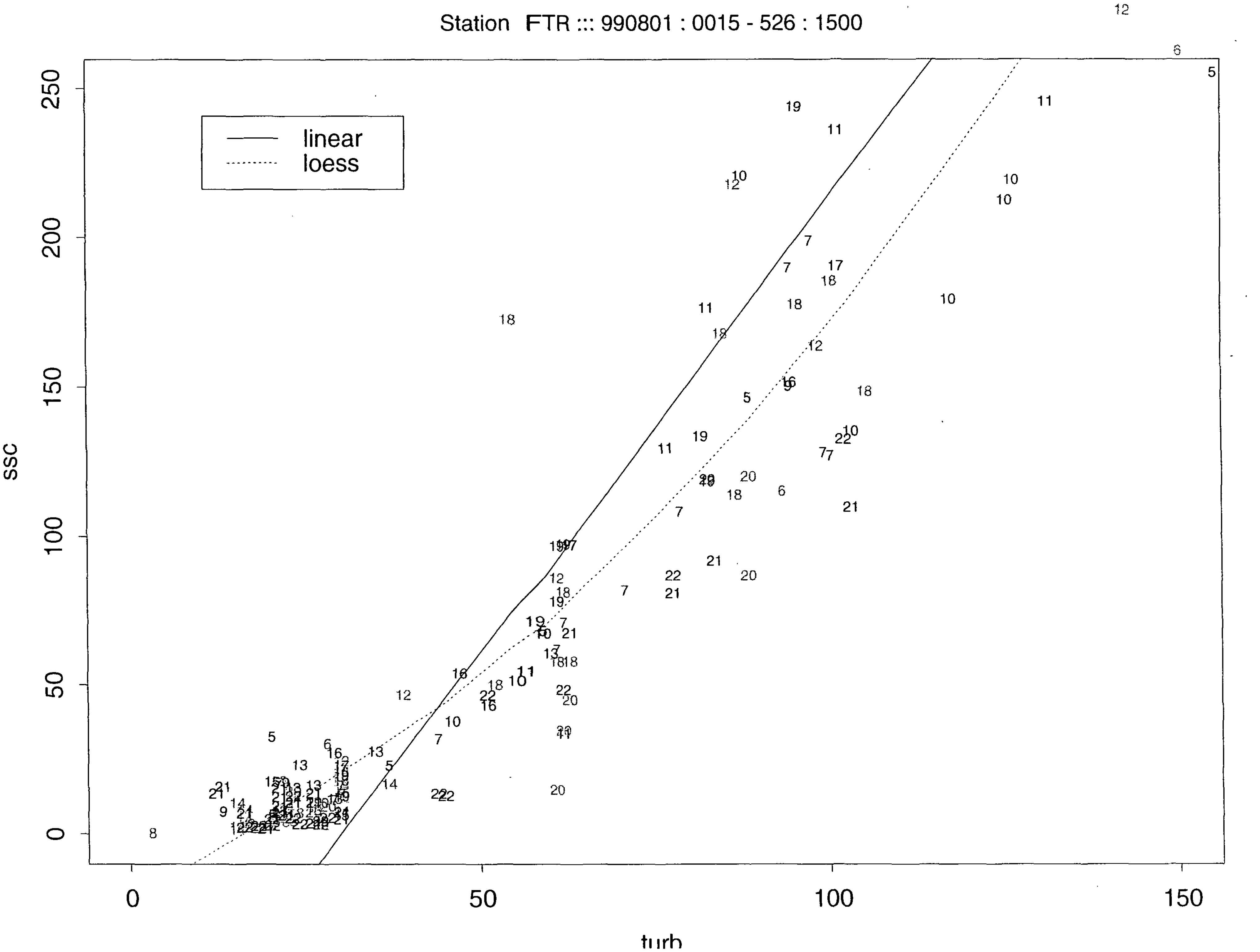
Station FTR ::: 990801 : 0015 - 526 : 1500
linear
loess
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50
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150
200
250
turb
0
50
100
150

Linear Regression Stats

Intercept:	-91.96
Slope:	3.06
Degrees of freedom:	213 total; 211 residual
Residual standard error:	89.4

Quadratic Regression Stats

Intercept:	-56.60
turb:	2.35
I(turb^2):	0.0014
Degrees of freedom:	213 total; 210 residual
Residual standard error:	83.4

Cubic Regression Stats

Intercept:	-46.14
turb:	2.04
I(turb^2):	0.0029
I(turb^3):	-1.74e-06
Degrees of freedom:	213 total; 209 residual
Residual standard error:	83.2

LOESS Regression Stats

Number of Observations:	213
Equivalent Number of Parameters:	4
Residual Standard Error:	82.56
Multiple R-squared:	0.97

Residuals:

min	1st Q	median	3rd Q	max
-618.6	-14.58	-2.629	11.45	364

For hydrologic year 1999, 2.5 million kg of suspended sediment was estimated to have traveled down Freshwater between the dates 1/13/99 to 8/1/99. For hydrologic year 2000, the linear estimate (refer to above plot) and LOESS models both predicted an annual suspended load on the order of 4.5 million kg between 11/10/99 to 5/26/00. One cannot compare the two load estimates directly because the data set was much more complete for HY 2000, keeping in mind also that both years were very different hydrologicly. A visual test as to whether the turbidity - suspended sediment relationship is changing, of which the load estimates are fundamentally based, was to plot the HY 1999 and HY 2000 samples on a single plot. This was carried out and is shown in the section after the storm loads, which are presented next.

DESCRIPTOR	LINEAR	LOESS
NUMBER OF OBSERVATIONS	213	213
R-SQUARED	0.96	0.97
RESIDUAL STANDARD ERROR	89.4	82.6
PREDICTED LOAD (kg)	4554629	4479326
PREDICTED LOAD (kg/ha)	1322	1300
PREDICTED LOAD (ton/mi2)	378	372

Note: Freshwater Watershed Area Above Study Site: 13.3 mi^2 (3445 ha)

STORM LOAD PREDICTION

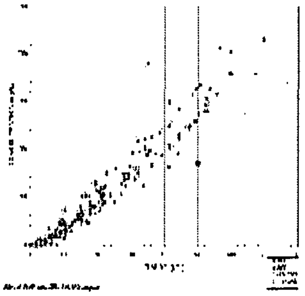
The six largest storms of HY 2000 were selected based on peak turbidity and/or stage. The sum total of all storm load estimates is 4001600kg. The LOESS model predicted an annual load of 4479326kg (refer to previous section). The sum total estimated storm load is 89.3% of the LOESS annual load estimate. Just as was revealed in the HY 1999 data set; the majority of the suspended load is indefinitely mobilized during a relatively short time of the year, during significant storm events. The table below summarizes the data for each of the six storm events.

STORM	START DATE	END DATE	LOAD ESTIMATE (kg)	NUMBER OF SAMPLES	PEAK STAGE (ft)*	PEAK TURBIDITY (NTU)*
1	11/29/99 1630	12/01/99 0800	101274	6	2.152	500
2	01/10/00 1200	01/12/00 2300	1311497	25	4.693	696
3	01/13/00 1000	01/15/00 1800	1061939	14	4.622	583
4	01/15/00 2130	01/17/00 0000	182757	8	2.872	331
5	02/14/00 0000	02/15/00 1330	1020729	40	4.404	628
6	02/26/00 1700	03/02/00 0000	323404	16	2.783	263

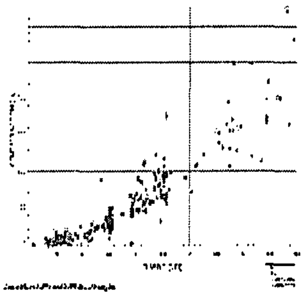
*_NOTE: PEAK STAGE AND PEAK TURBIDITY MAY NOT HAVE OCCURED AT THE SAME SAMPLE TIME INTERVAL!!_

PLOT OF 1999 AND 2000 ISCO SAMPLES

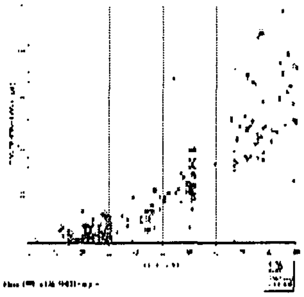
One plot I thought would be interesting to show, that Jack Lewis recommended, was a plot of the combined samples from HY 1999 and HY 2000. If there is a significant trend in sediment transport that could be distinguished from year to year, it should be evident on this plot. The three plots below show both HY 1999 and HY 2000 sediment samples distinguished by marker type and color. Circles have been placed around data that has either been coded for possibly corrupt suspended sediment concentration or turbidity (as explained in the codes documentation file). The plots tend to show that the data from both years are in agreement. Each data point seems to be within the observed variance of either individual data set.



Turbidity Scale: 0-800 NTU
Suspended Sediment Scale: 0-2500mg/L



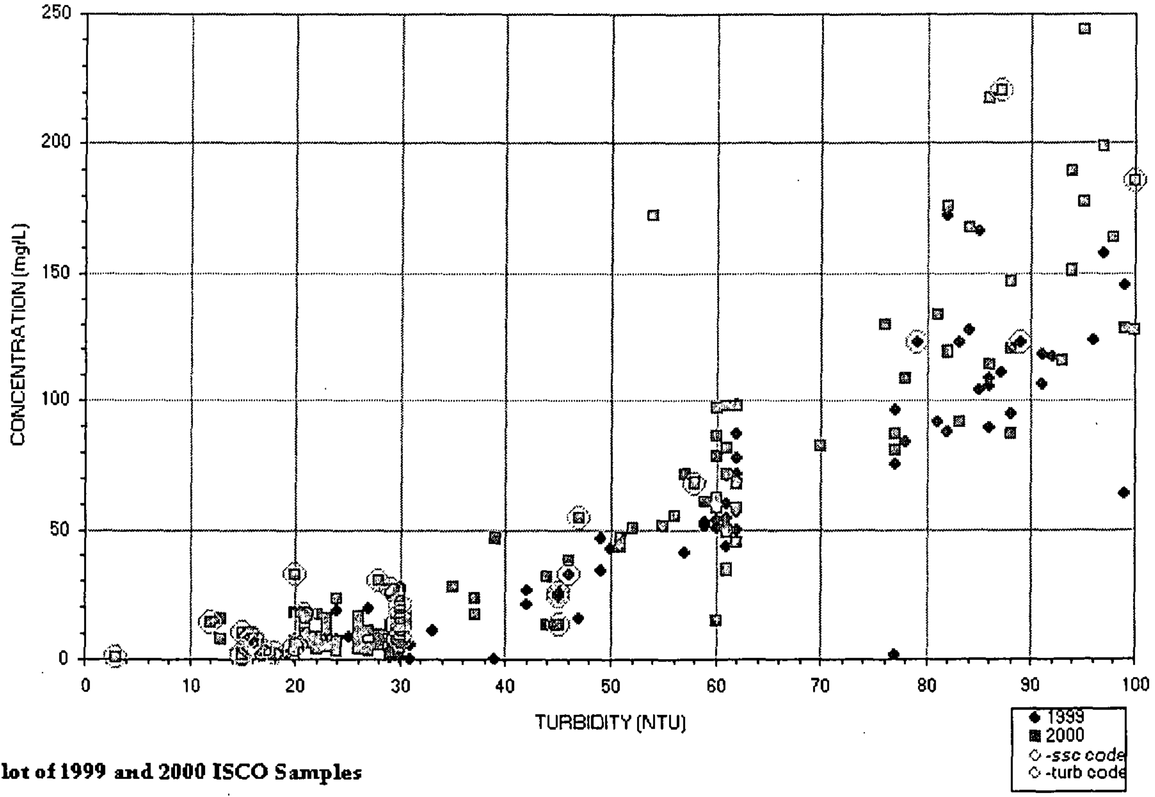
Turbidity Scale: 0-200NTU
Suspended Sediment Scale: 0-650mg/L



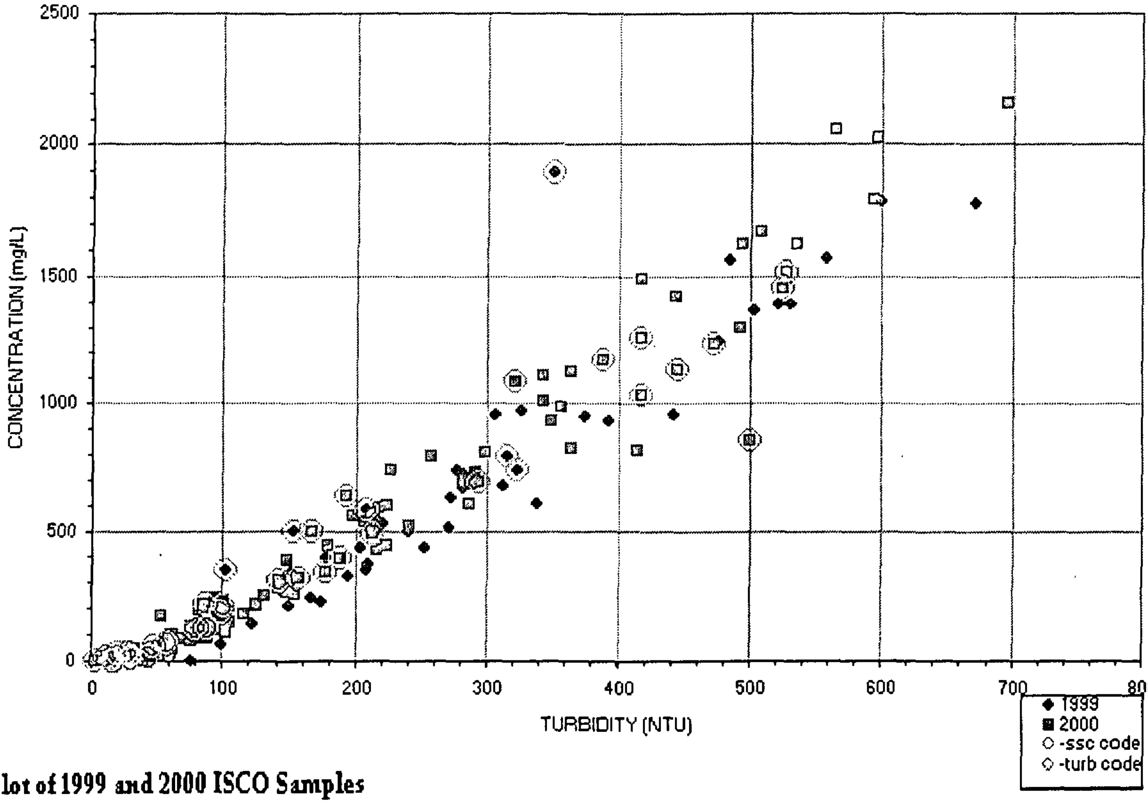
Turbidity Scale: 0-150NTU
Suspended Sediment Scale: 0-250mg/L

DURATION OF TURBIDITY THRESHOLD EXCEEDENCE

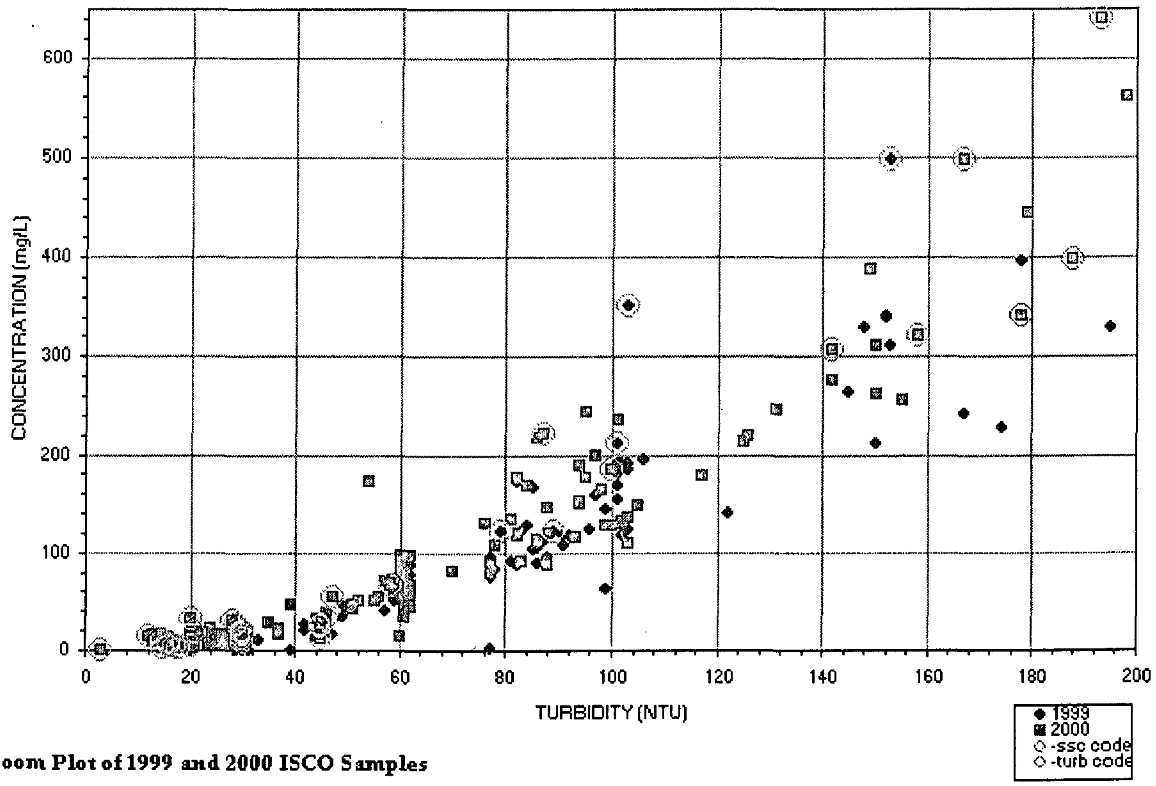
> "*Turbidity:* High concentrations of suspended sediment may delay or divert spawning runs and in some instances can cause avoidance by spawning salmon (Smith 1939; Servizi et al. 1969; Mortensen et al. 1976). Salmonids were found to hold in a stream where the suspended sediment load reached 4,000 mg/L (Bell 1986). Though high sediment loads may delay migration, homing ability does not seem to be adversely affected (Murphy 1995). Cowlitz River chinook salmon returned to the hatchery seemingly unaffected by the sediments derived from the eruption of Mount St. Helens, Washington although in the highly impacted Toutle River tributary of the Cowlitz, coho salmon did stray to nearby streams for the first two years following the eruption (Quinn and Fresh 1984). ... Turbid waters have been mentioned as affecting migration but



Plot of 1999 and 2000 ISCO Samples



Plot of 1999 and 2000 ISCO Samples

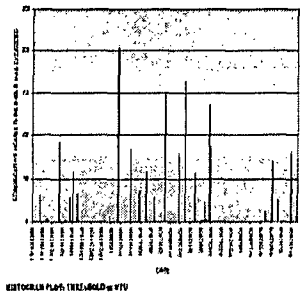


Zoom Plot of 1999 and 2000 ISCO Samples

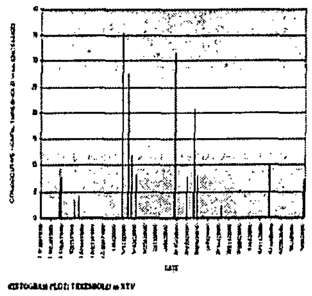
> little documentation is available in the literature. Thomas (1975) found fry migration increased as turbidity increased. Lloyd et al. (1987) found that turbid streams were avoided by juveniles except when the fish must pass through them on migration routes. There is also some evidence that diel migrations of salmonids is influenced by turbidity. Many salmonids tend to migrate during the evening hours (Burgner 1991), presumably to avoid predation. However, in streams with higher turbidity, migrations may be evenly dispersed over day and night."

MANTECH REPORT: ***"An Ecosystem Approach to Salmonid Conservation"*** **TR-4501-96-6057. December 1996.**

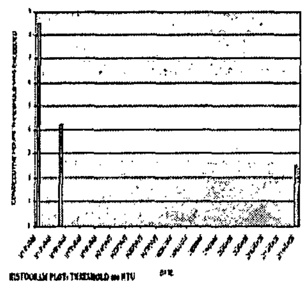
This last series of plots are histogram plots of exceedence of a given turbidity threshold. These plots have come out of an interest in research conducted by Newcombe and McDonald (1991) and Newcombe and Jensen (1996). These researchers compiled literature on the physical and biological response of fish to elevated levels of suspended sediment. Due to the nonexistence of continuous suspended sediment data to apply to the models presented by Newcombe and McDonald (1991) and Newcombe and Jensen (1997) other researchers have tried to extend the model for turbidity thresholds. This must be done carefully because the turbidity-suspended sediment concentration relationship may be well defined for a specific site, the relationship is site specific and depends upon many variables such as flow regime and geology. The greater the threshold and the longer the time of exposure the greater the biological stress, the most stressful of course being death. Clearly turbidity is a less desirable water quality variable, compared to suspended sediment concentration, from the standpoint that threshold levels will not be universal among all sites, but it is desirable from a the standpoint of data collection. Measurement of continuous turbidity and development of a relationship between turbidity and suspended sediment concentration is much more feasible for a specific site compared with continuously monitoring suspended sediment (imagine the lab work involved with that!). A well defined relationship between turbidity and suspended sediment concentration is essential in this monitoring approach, especially if management models like ones proposed by Newcombe and McDonald (1991) or Newcombe and Jensen (1997) are to be extended to turbidity thresholds. One of the first data sets that has been extensive enough to adequately apply these models is clearly here at Freshwater. The author of this web page (Ben Bray) wrote a FORTRAN processing routine that outputs histogram data (for importing into Microsoft Excel) given user defined turbidity levels. The program requires the standard .flo file for processing. DOWNLOAD a copy of the FORTRAN turbidity threshold routine EXECUTABLE or FORTRAN90 SOURCE CODE so that you may produce your own turbidity threshold histogram plot. Two examples are shown below. Instructions for use of this program may also be obtained by clicking here.



Turbidity Threshold: 25NTU



Turbidity Threshold: 80NTU



Turbidity Threshold: 380NTU

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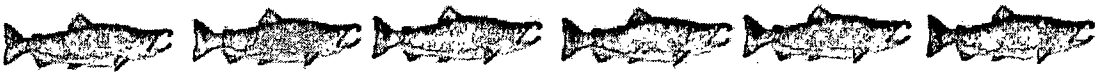
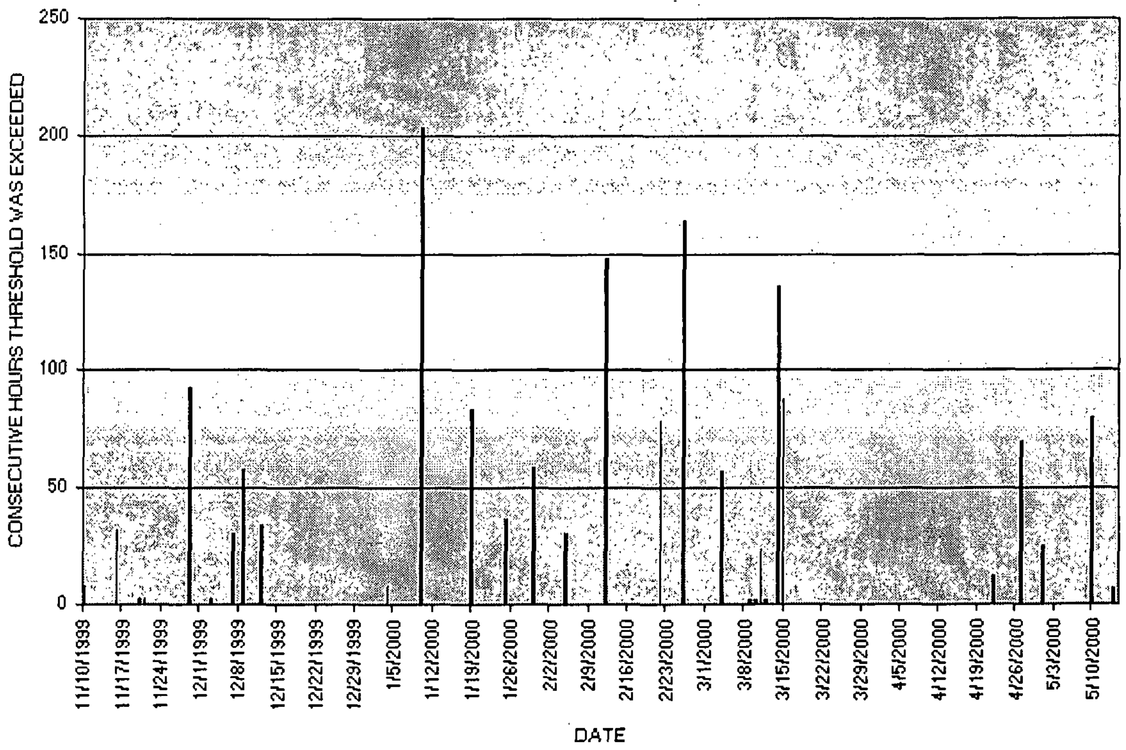
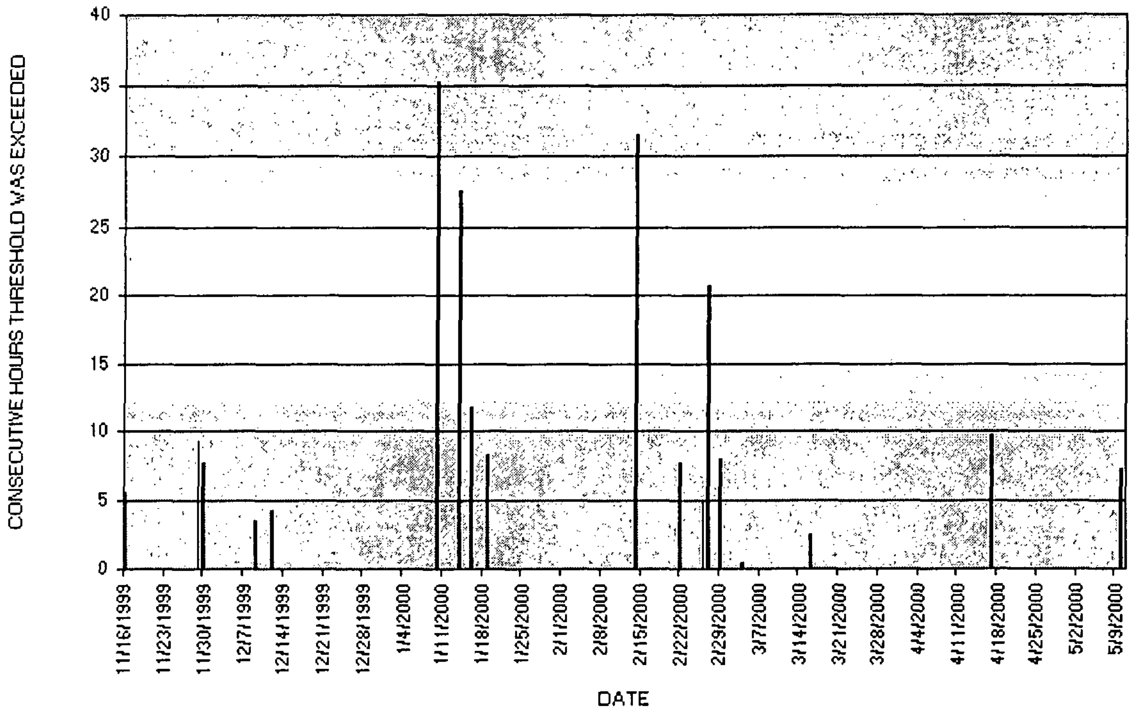


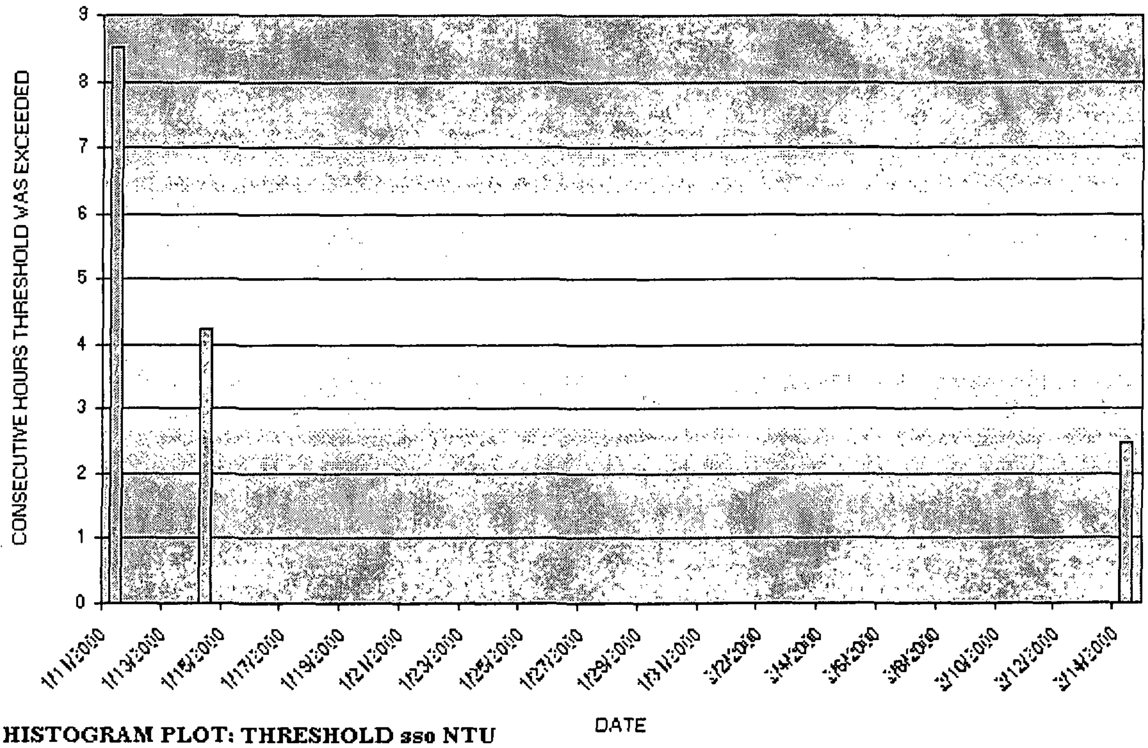
Freshwater // Last updated on October 19, 2000, by Ben Bray



HISTOGRAM PLOT: THRESHOLD 25 NTU



HISTOGRAM PLOT: THRESHOLD 50 NTU



HISTOGRAM PLOT: THRESHOLD 350 NTU

Freshwater Creek, California...

Annual and Storm Analysis, Turbidity Threshold Sampling (TTS)

The equipment for this monitoring station was purchased by Salmon Forever. The station was cooperatively installed by the Forest Service, Redwood Sciences Laboratory (RSL), Salmon Forever, Humboldt State University Fisheries Professor Terry Roelofs, and members of the Freshwater community. Because the monitoring station was activated on January 13, 1999, a significant portion of hydrologic year 1999 was not included in the data and, therefore, not included in the analysis presented below. For example, the first major storm event of the hydrologic year is not included in the annual load estimates presented. Although this storm, which peaked on November 21, had the highest peak of the 1999 hydrologic year, no flow or sediment data were collected and no attempt was made to quantify the amount of sediment delivered.

The purpose of this analysis was to estimate sediment loads using the relations between suspended sediment concentration, turbidity and discharge in Freshwater Creek. The analysis as presented below was carried out at RSL on a Unix operating system using S-Plus and Perl. The majority of the analysis tools and plotting routines were written in S-Plus because of its powerful ability to manipulate and graphically represent the data.

Instrumentation included a Campbell data logger, a pressure transducer for recording stage height (water depth), an ISCO sampler to extract pumped sediment samples from the stream, and an infrared turbidity probe. The pressure transducer was calibrated in the field, and the electronic measurements were adjusted to observations made systematically in the field when appropriate. Stage height and turbidity were recorded at 15-minute intervals. Manual discharge measurements were made in the field to develop a relationship between stage height and discharge. Pumped samples were collected automatically at pre-determined turbidity thresholds according to a program loaded in the data logger. These sample bottles were analyzed for sediment concentration at RSL and the Salmon Forever Sunnybrae Sediment Lab using methods described in *Standard Methods for the Examination of Water and Wastewater.* The turbidity measurements recorded by the Campbell data logger were converted to suspended sediment concentrations using regressions based on the pumped sample concentrations. The regression methodology is described in following sections of the web page.

Depth-integrated water/sediment samples were also collected at various stages so that the point samples taken by the ISCO sampler could be adjusted to account for sediment delivered across the entire cross section. However due to an insufficient number of depth-integrated samples, this portion of the analysis was not carried out. Thus all load estimates presented are based on the point samples taken by the ISCO sampler. If an adjustment based on an adequate number of samples were to be carried out, it is likely that it would result in higher sediment loads than those presented below, because sediment concentrations are expected to be greater near the stream bed.

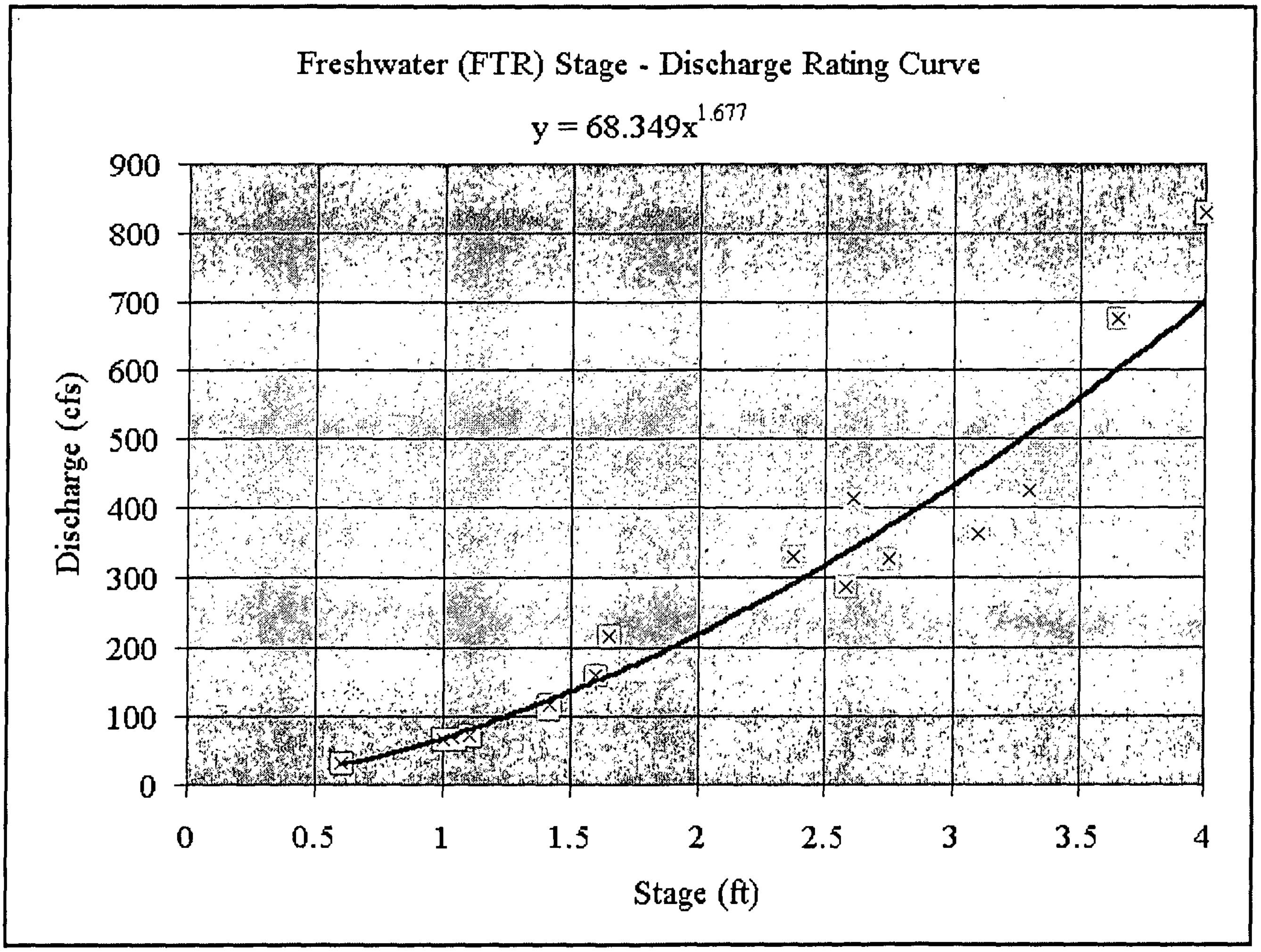
Development of the Stage - Discharge Rating Curve at the Freshwater Station

---

A prerequisite for estimation of the sediment load is development of a discharge rating curve for converting stage height to water discharge. This was carried out using the standard method of discharge measurement using either a Price AA or pygmy current meter to measure water velocities at the stream cross-section (refer to *Stream and Channel Reference Sites: An illustrated guide to field technique* by C.C. Harrelson, C.L. Rawlins, and J.P. Potyondy, USDA Forest Service General Technical Report RM-245, April 1994). Discharge was computed by summing up the products of velocity and partial cross-sectional area over the entire cross-section. To obtain a discharge rating curve, a power relationship, as shown in the figure below, was fit to the data presented in the following table. The power relationship assumes a cross-section that is *non-deforming* in time. However, the cross section at the Freshwater station was not located on bedrock and is directly downstream from a meander bend in the channel. These characteristics of the sampling site are clearly undesirable and add substantial uncertainty to the load estimates given in the following sections of this web page. More discharge measurements over time would quantify the uncertainty involved with this aspect of the analysis.

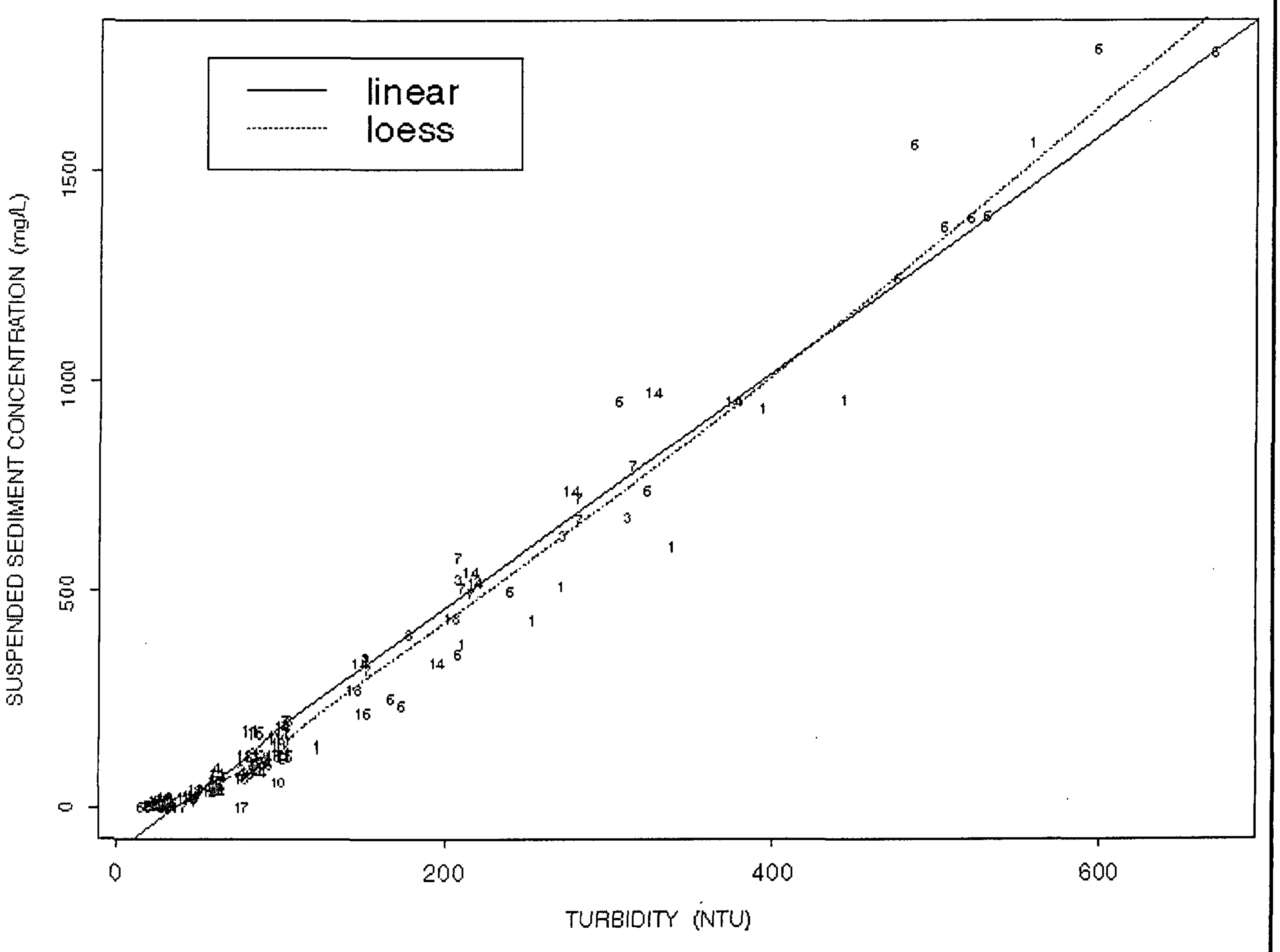
Stage - Discharge Rating Curve Data

DATE	TIME	QUALITY	STAGE (ft)	DISCHARGE (cfs)
12/17/98	1545	good	0.60	31.37
01/16/99	1635	good	1.05	67.09
01/19/99	1300	fair	1.60	160.18
01/23/99	1116	good	2.37	328.38
01/24/99	1000	good	1.41	109.80
02/06/99	921	poor	1.11	74.25
02/06/99	1009	poor	1.65	215.46
02/06/99	1054	poor	2.61	413.01
02/06/99	1150	poor	3.65	674.87
02/06/99	1306	fair	4.00	831.00
02/06/99	1524	good	3.30	423.70
02/06/99	1602	good	3.10	363.17
02/06/99	1701	fair	2.75	325.92
02/06/99	1758	fair	2.58	285.34
02/08/99	1556	good	1.42	116.50
02/15/99	905	good	1.01	68.60



Annual Regression Discussion

This first plot shows the complete data set used for the annual load estimates. The numbers correspond to bottles analyzed in a given dump (batch of up to 24 bottles). For example, all number 14's correspond to bottles analyzed in dump 14. A total of 18 dumps, including approximately 154 bottles, were used for the regression shown in plot 1.



Plot 1: Annual Linear Regression and Loess Regression.

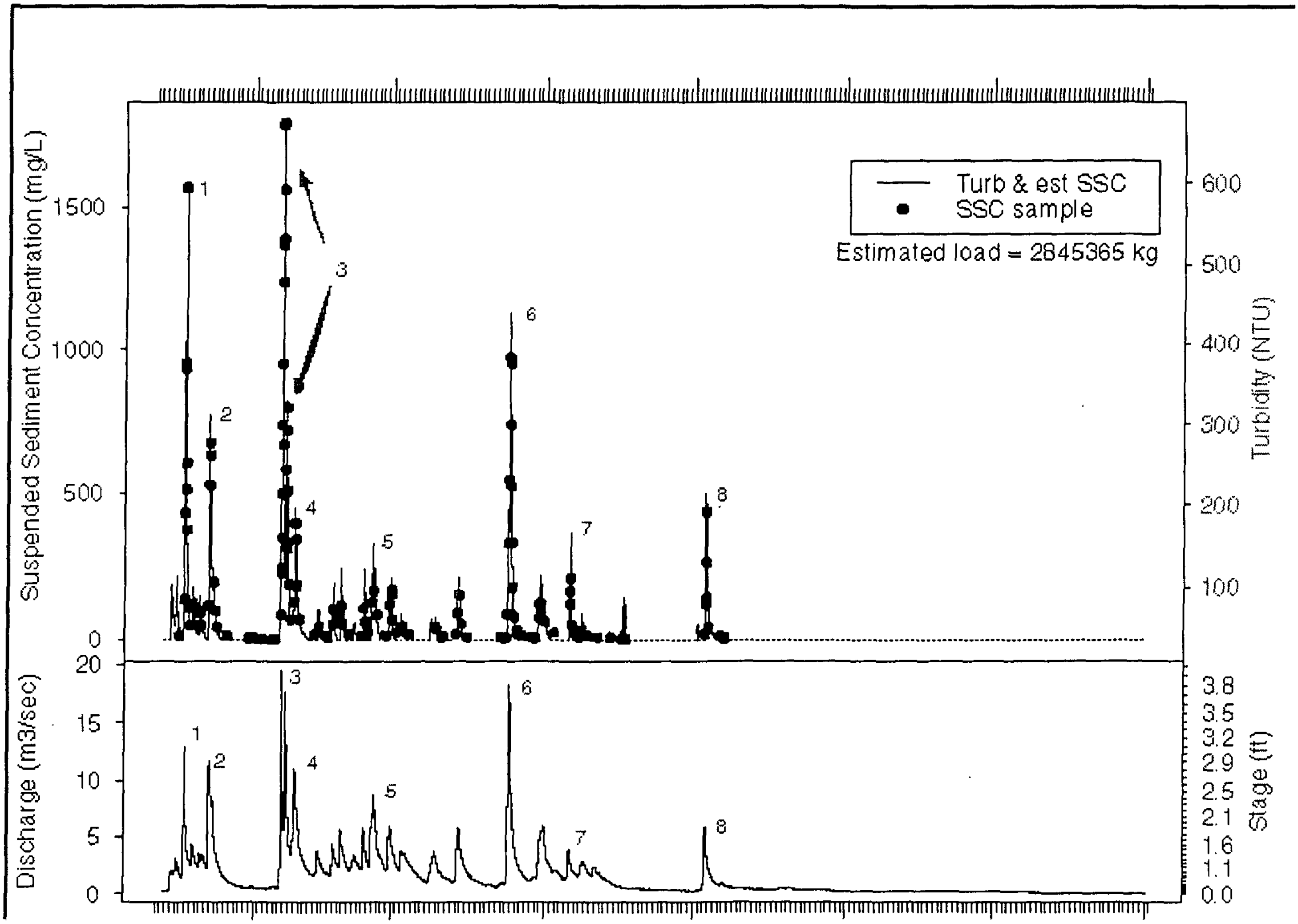
A linear equation seemed to do a poor job in fitting the lower portion of the data set. A quadratic, a cubic polynomial, and a smooth loess were also fit to the data set. "Loess", short for LOcal regrESSion, is flexible tool for fitting almost any shape curve. There is a good description of loess in William S. Cleveland's book "Visualizing Data" (Hobart Press, 1993). The loess fit was determined to give the best fit to the data set. The results of the linear and the loess fit are given below including the annual load predictions. Notice that the linear fit gives a fairly good

R-SQUARED value and that the linear and loess predictions are very close.

DESCRIPTOR	LINEAR	LOESS
NUMBER OF OBSERVATIONS	154	154
R-SQUARED	0.971	0.980
RESIDUAL STANDARD ERROR	65.3	57.17
PREDICTED LOAD (kg)	2845365	2800470
PREDICTED LOAD (kg/ha)	826	813
PREDICTED LOAD (ton/mi2)	236	232

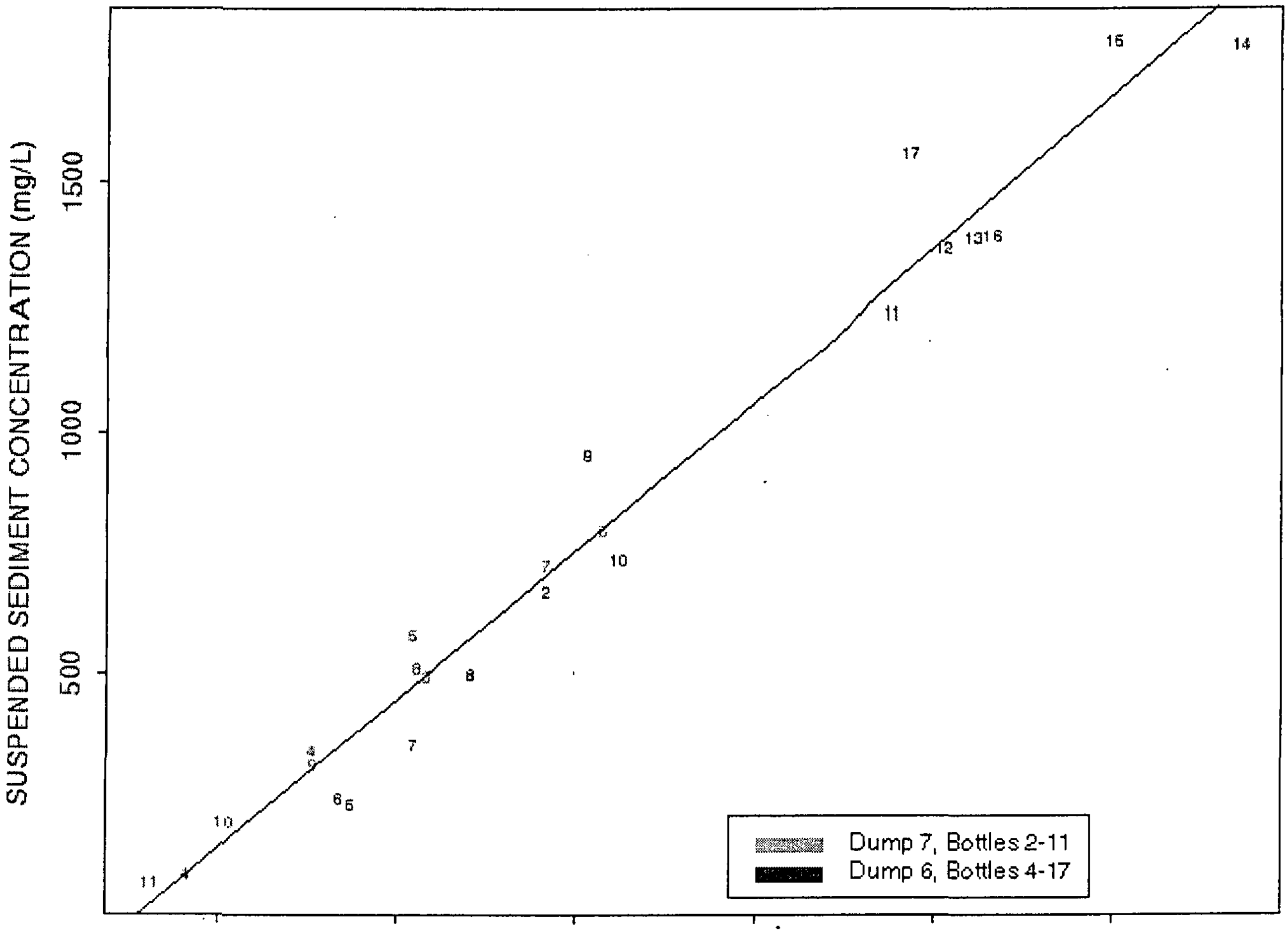
Note: Freshwater Watershed Area Above Study Site: 13.3 mi2 (3445 ha)

Plot 2 (shown below) summarizes the entire data set for hydrologic year 1999 at Freshwater (January 13, 1999 to August 1, 1999). The upper plot is the sedigraph and the lower plot is the hydrograph. The sedigraph is based on the linear regression model presented above where suspended sediment concentration is assumed to be a linear function of turbidity. The suspended sediment concentration is shown on the upper left axis (in mg/L) and the turbidity scale is on the right axis (in NTU). For the entire period, the load estimate (shown below the legend) matches the prediction made by the linear model presented above. The sedigraph peaks tended to occur before the hydrograph peaks.

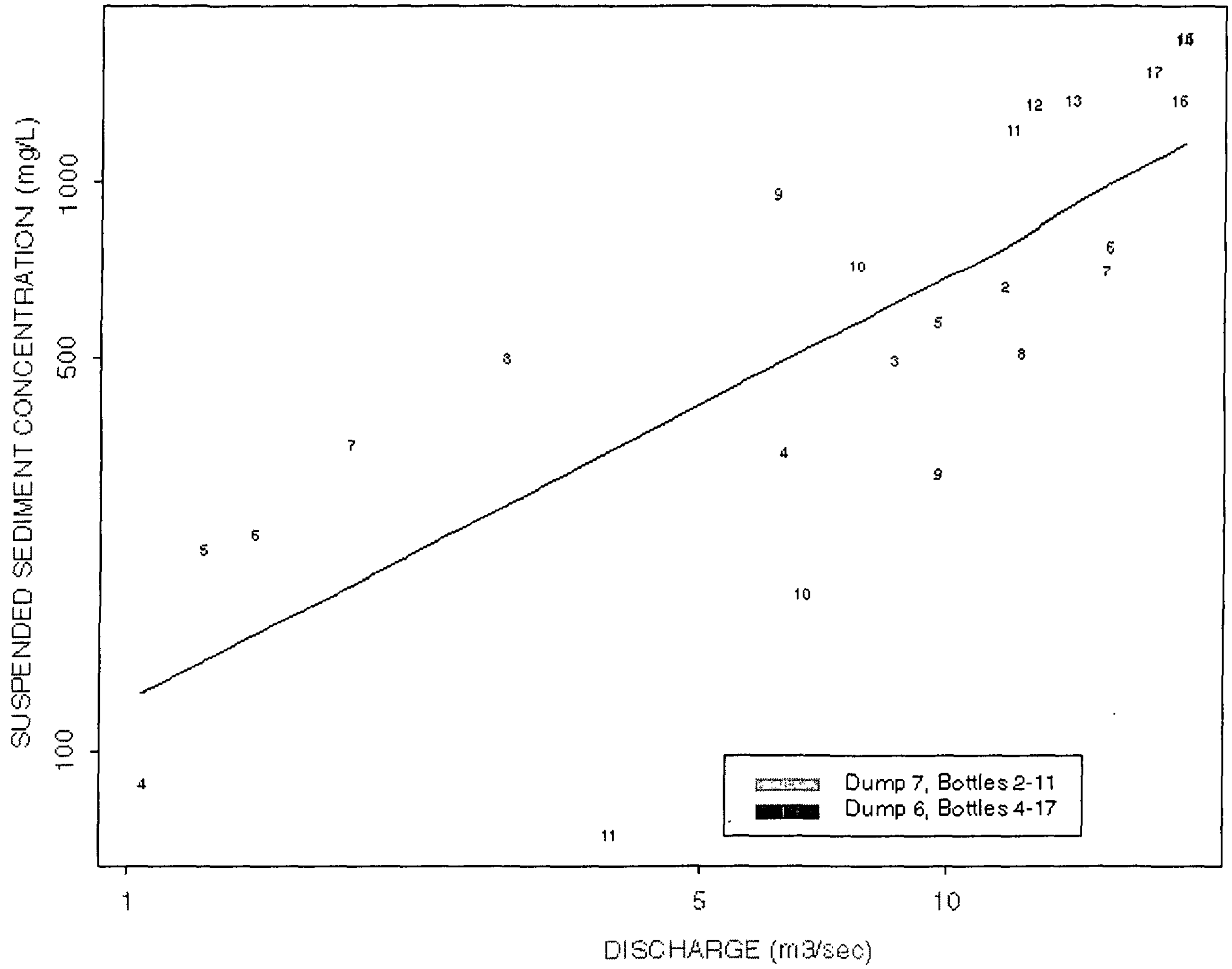


Individual Storm Analysis

How well does the loess regression predict the load delivered by individual storms? Eight storms were selected for analysis (these storms are numbered 1-8 on plot 2 above). Each storm period was first designated. Then a linear regression was carried out on the samples analyzed under the dump(s) that corresponded to the designated storms. In some cases a rating curve relating discharge and suspended sediment was used where the linear regression between suspended sediment and turbidity predicted negative values. This was often at the very beginning or end of the storm. As an example, we shall select Storm 3 (start:02/06/99, 0300 hrs; end:02/08/99, 1315 hrs). The initial regression using *all* ISCO sample bottles taken during the storm was carried out and is shown below in plot 3.

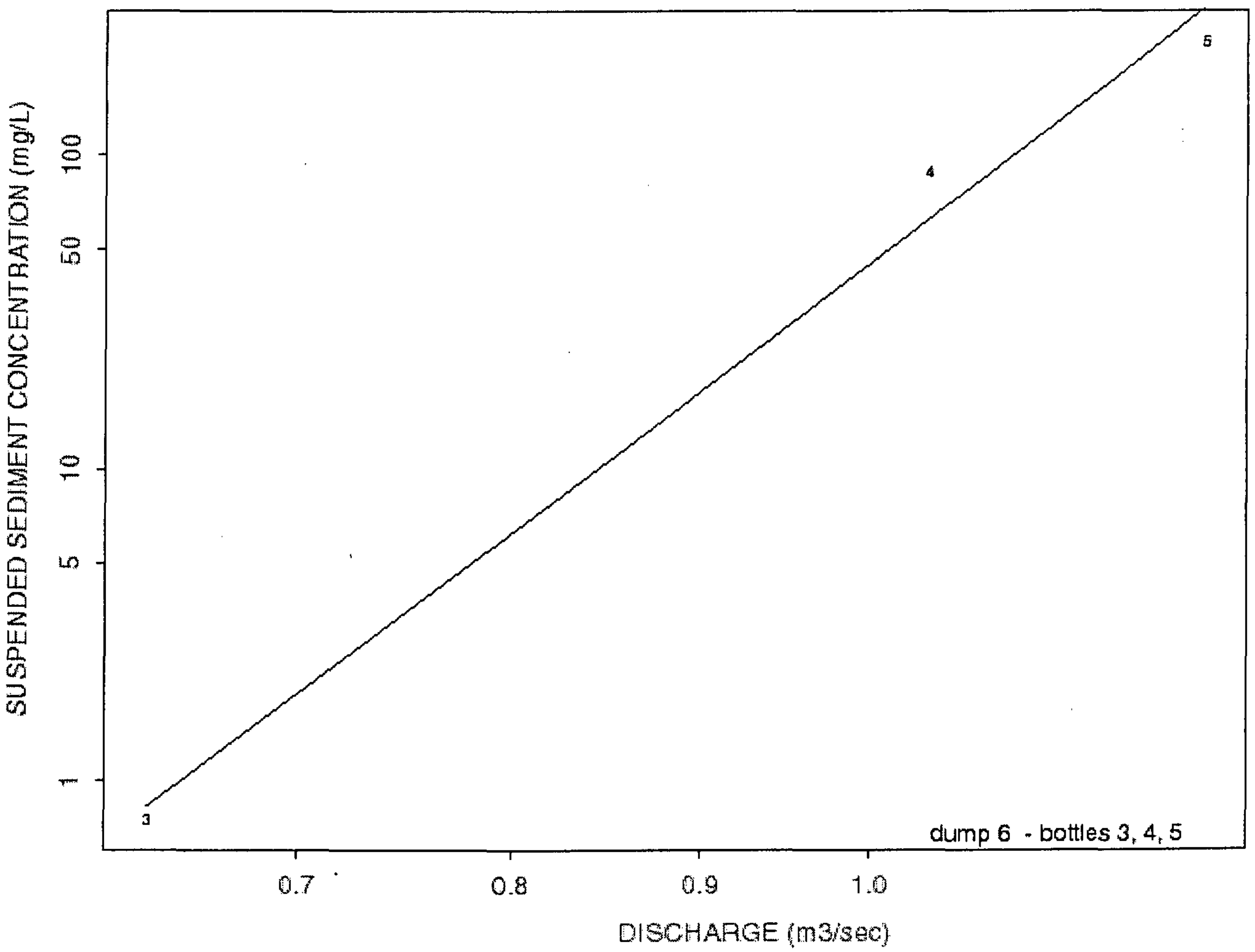


However, this linear regression model predicted negative values at the very beginning *and* end of the storm. A power relationship between discharge and suspended sediment was then determined using the samples taken for Storm 3. This plot is shown below as plot 4. The plot shows a characteristic hysteresis loop in the suspended sediment - discharge rating curves. This can be seen by tracing the bottle numbers in plot 4 for either dump.



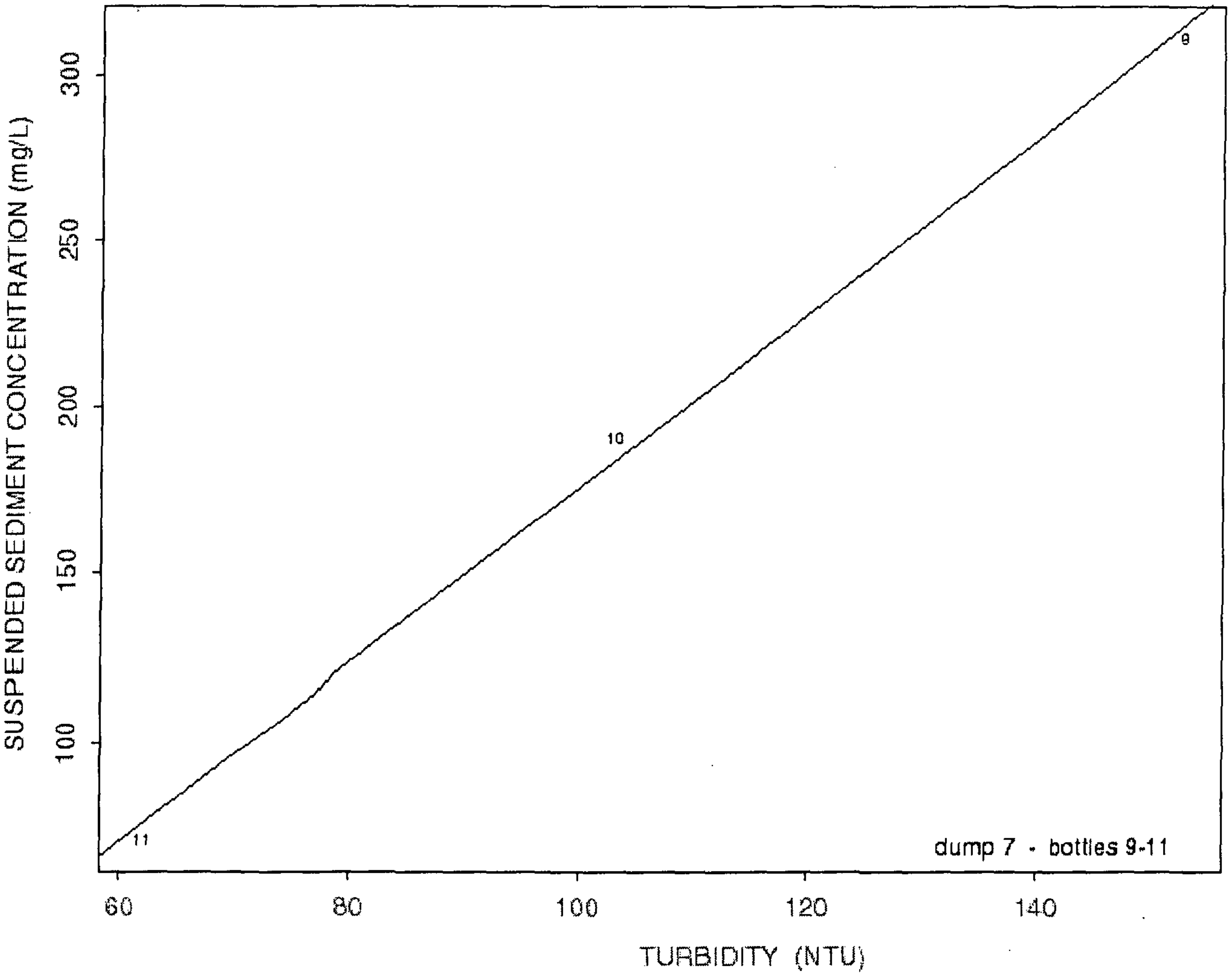
Plot 4: Discharge and Suspended Sediment Rating Curve, All Bottles.

Notice the hysteresis loop is formed because a greater suspended sediment concentration was observed on the rising limb of the hydrograph, while the suspended sediment concentration was lower for a given discharge on the falling limb of the hydrograph. Because the objective was to correct the negative predictions at the front end of the storm, another rating curve was developed using only the first three sample bottles taken. This rating curve is shown below in plot 5.



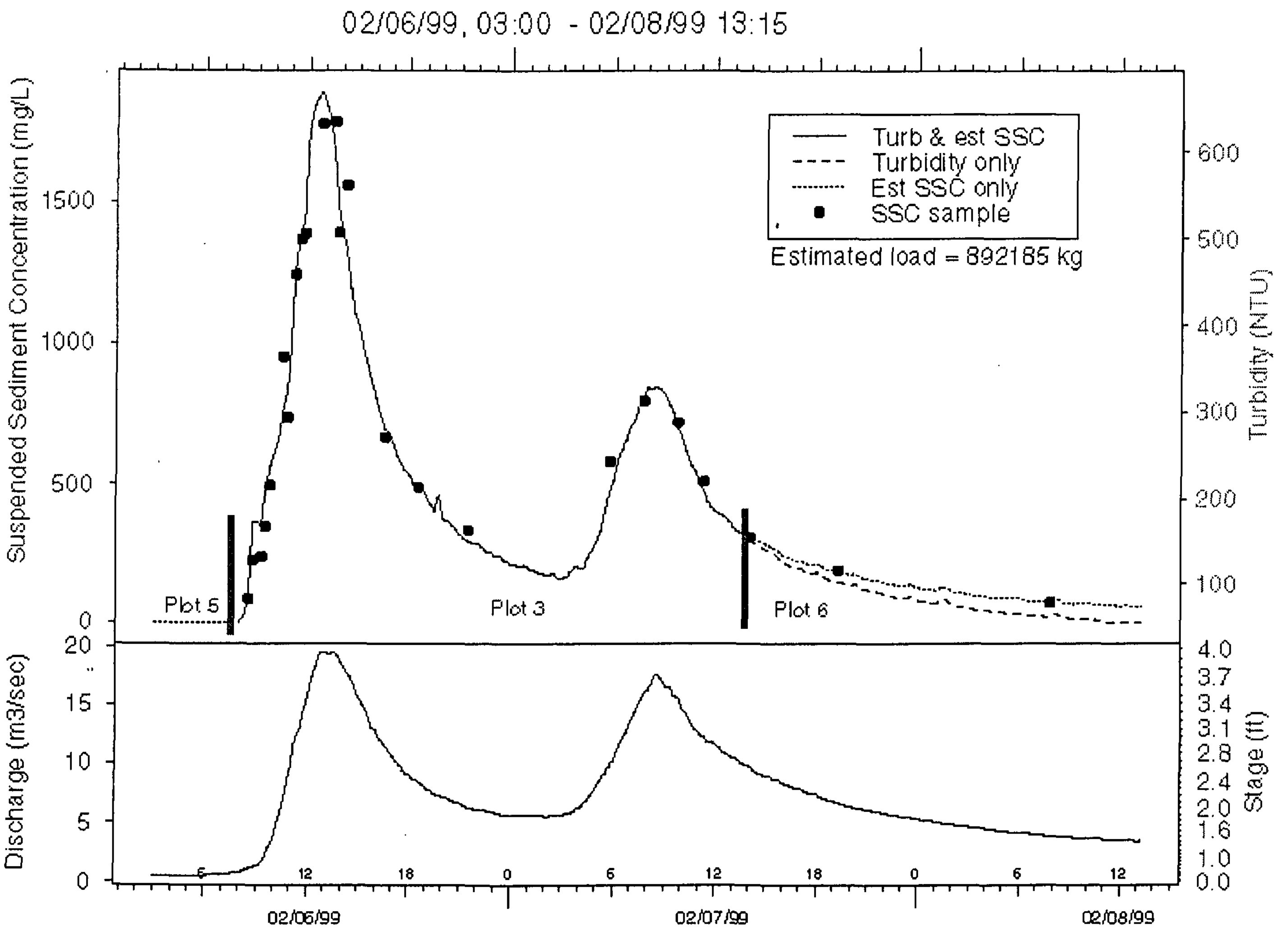
Plot 5: Discharge and Suspended Sediment Rating Curve

Finally, a regression using suspended sediment concentration and turbidity values from the last three sample bottles were used to remove the negative predictions at the end of the storm given by the original regression (refer to plot 3 above). This final regression is shown below as plot 6.



Plot 6: Selected Regression of Suspended Sediment vs. Turbidity, Storm 3.

All three of these relationships are then pieced together to form the final estimate for the storm. Plot 7 (below) shows the resulting sedigraph and hydrograph for Storm 3. Notice the load estimate for the storm is given under the legend.



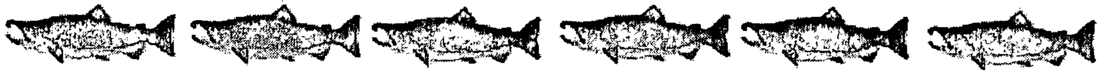
Plot 7: Storm 3, Complete Sedigraph and Hydrograph.

The table below shows each storm estimate compared to an estimate computed from the annual loess fit. Notice that all eight storms accounted for 86% of the total annual load estimate. As shown in the table below, the loess fit gave fairly good estimates for individual storms with the largest deviation observed to be 28%. The deviations are explained by observing the distribution of points in plot 1. By observing how the dumps (i.e. ISCO sample bottles) corresponding to a given storm fall in relation to the loess curve, one can predict whether the loess model will under- or over-estimate the sediment load delivered by the storm event. The bias in using an annual relationship to estimate individual storms was limited in this example because there was relatively little scatter in the annual data set.

STORM	LOAD ESTIMATE (kg) STORM REGRESSION	LOAD ESTIMATE (kg) ANNUAL LOESS	% DIFFERENCE
1	273493	303014	10.8%
2	309508	277954	-10.2%
3	892185	852181	-4.5%
4	212461	179649	-15.4%
5	56836	41171	-27.6%
6	614202	561425	-8.6%
7	23069	20070	-13.0%
8	60676	56878	-6.3%
TOTAL	2442430	2292342	-6.2%

LOESS LOAD ESTIMATE OF ANNUAL LOAD: 2845365kg

TOTAL ESTIMATED STORM LOAD AS A PERCENTAGE OF ESTIMATED ANNUAL LOAD: 85.8%



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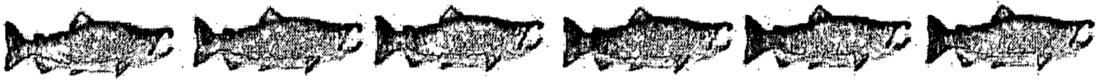
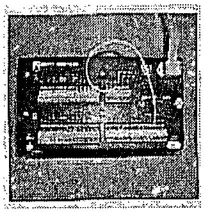


Freshwater // Last updated on October 19, 2000, by Ben Bray

Freshwater Creek, California...

Turbidity Threshold Sampling



Rand Eads

The Importance of Automated Data Collection

The ability to collect useful information about suspended sediment transport and water discharge is dependent on the timing and frequency of data collection during storms. All river systems, particularly smaller watersheds that respond very quickly to rainfall with peak discharges often occurring shortly after the onset of precipitation, benefit from automated data collection. Although it is possible to rely solely on manual measurements, important storm flows are infrequent and difficult to predict, and when they do occur, trained personnel may not be available to collect the required information. Most of the suspended sediment is transported during storms (approximately 86% of the estimated sediment transport in 1999 occurred during the 8 largest storms). Infrequent, systematic manual sampling will not provide adequate information to make credible suspended sediment load estimates under these conditions. As of yet, there is no reliable method to directly measure suspended sediment concentration in the field. A common method to estimate suspended sediment loads relies on water discharge to determine the sampling frequency during storms. Usually water discharge is not a good predictor of sediment concentration for rivers and streams that transport the bulk of their sediment load as fines because the delivery of sediment to the channel from hillslopes, roads, and landslides is highly variable. For rivers that transport mostly sand, water discharge and concentration are more closely coupled because the transport of sand particles depends on stream power and the availability of sediment stored in channel bars and flood plains. A sampling scheme that employs a parameter well correlated to suspended sediment concentration, such as turbidity, can improve sampling efficiency by collecting physical samples that are distributed over a range of rising and falling concentrations (see Lewis and Eads 1996 and 1998). The resulting set of samples can be used to accurately determine suspended sediment loads by establishing a relationship between sediment concentration and turbidity for any sampled period and applying it to the continuous turbidity data.

How Turbidity Threshold Sampling Works

Turbidity is an optical measure of the number, size, shape, and color of particles in suspension. A number of manufacturers offer turbidity probes that can be deployed on a continuous basis in streams.The optical properties of sediment, mainly size and shape, have a large influence on the magnitude of the turbidity signal. For instance, sand particles return a much lower turbidity signal for a given concentration than silt and clay particles of the same concentration. The Turbidity Threshold Sampling scheme (TTS) distributes turbidity thresholds, points at which physical samples are collected, across the entire range of expected rising and falling turbidities. Contamination of turbidity probe's optics by debris, algae, or macroinvertebrates can lead to a noisy, or progressively increasing, turbidity signal. For many temperate locations, biofouling occurs during non-storm periods when water temperature and solar energy are elevated. Careful design of the turbidity probe's housing and periodic manual cleaning of the optics can eliminate most fouling.

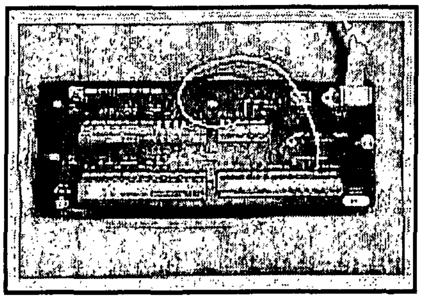
Turbidity thresholds are selected by taking into consideration the maximum expected turbidity value for a stream, the range of the turbidity probe, and the number of desired physical samples based on the magnitude of the storm. In our experience, using a square-root scale to distribute the thresholds provides an adequate pairing of turbidity-concentrations to produce acceptable regressions. For the smallest storms, three or four samples should be adequate, while large events may produce 12 to 18 samples. Different sets of thresholds are used when turbidity is rising and falling, with more thresholds required during the much more prolonged falling period. The user can fine-tune the distribution to maximize efficiency. A set of rules, in addition to the pre-defined turbidity thresholds, aids in reducing sampling during short duration turbidity spikes, ensures that a "startup" sample is collected at the beginning of a storm, and defines reversals in turbidity. The rules permit continued sampling when turbidity levels exceed the turbidity probe's range, and they allow collection of non-threshold, manually triggered samples to be paired with depth-integrated samples or to augment sample numbers if desired.

Closely spaced turbidity measurements produce interesting trends in sediment transport such as spikes superimposed on the storm turbidigraph that often indicate landslides or streambank failures upstream. In the case of nested watersheds, the timing and magnitude of these sediment pulses may provide additional information about cumulative effects, or dilution, downstream. Authenticity of these turbidity spikes is confirmed when physical samples taken during the spikes have higher concentrations than surrounding samples.

Instrumentation

Data Logger and Sampling Logic

A programmable data logger is required to make the required sampling decisions. For remote locations, it is important that the data logger has low power requirements in order to preserve the battery's capacity. The TTS program only requires input information about stage and turbidity to decide what actions to take (Figure 1). Wake-up intervals are either set at 10-minutes for small, flashy watersheds, or at 15-minute intervals for larger basins. At the beginning of each wake-up interval, the turbidity probe, under control of the program logic, collects 60 measurements in 30 seconds. Next, the raw turbidity values are sorted and the median value is determined. We have found that these two operations effectively reduce outlier values. The program next collects 150 stage readings in three seconds from a pressure transducer and computes the mean stage. The mean stage is then compared against the minimum operating stage to determine if the turbidity probe and sampler intake are adequately submerged to allow sampling. If the program logic determines that a sample is required, based on the rules discussed above, it activates an automatic water sampler to collect one sample. At the Freshewater Creek site a tipping bucket rain gage and water temperature probe are also connected to the data logger to provide additional information. Finally, all pertinent records are written to data logger memory. The TTS logic, discussed above, has been developed for Campbell data loggers (mention of product names is not an endorsement by the USDA Forest Service).

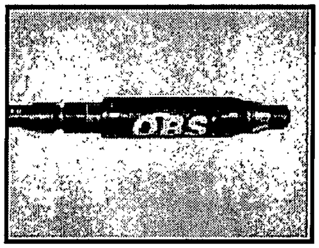


[102KB]

Figure 1. The Campbell data logger is capable of executing programs and storing data.

Turbidity Probe

The OBS-3 turbidity probe, manufactured by D&A Instrument Company (Figure 2), is a backscatter nephelometer that that emits infrared radiation (IR) into the water column. Infrared radiation does not penetrate far into the water so the volume of water and sediment actually sampled is small. The distance the IR penetrates the water depends on the amount of material in suspension; the penetration, or volume sampled, decreases with increasing concentration of material. The scattered IR returned to the sensor's detector is a function of particle size and shape and the number of particles in suspension. Comparisons made with different turbidimeters should be viewed with some skepticism due to inconsistencies in light sources, calibrations, and the sampled volume. Periodic calibration of the turbidity sensor in formazin standards is required to compensate for instrument drift or a scratched optical surface.



[66KB]

Figure 2. Turbidity is measured using the backscatter nephelometer OBS-3.

Turbidity Probe Housing

The turbidity probe housing reduces contamination from organics by shedding debris. The housing, if properly designed, can reduce hydrodynamic noise caused by turbulence and the entrainment of air or re-suspension of sediment close to the sensor. The housing also protects the sensor from direct impacts by large submerged organic debris (See Figure 3).

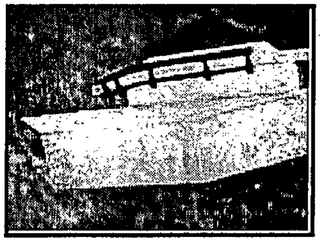


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Figure 3. The turbidity probe housing protects the sensor and improves data collection.

Sampling Boom

The boom positions the turbidity probe and sampler intake at the appropriate position and depth in the stream. Since the boom is articulated, large floating organic debris can, on impact, lift the vertical arm of the boom to the surface and pass underneath. Increasing water velocity and depth pushes the vertical boom arm downstream, raising the turbidity sensor higher in the water column. (See Figure 4.) A counterweight prevents the boom from skipping on the water surface. The highest probability of contamination by organics, and resulting loss of data, occurs during flood stages when organic material is recruited from flood plains. A bank-or bridge-mounted retrievable boom is required for all but the smallest streams to allow debris removal during high flows. The depth of the turbidity probe can be adjusted as needed to position the probe above the zone of bedload transport and below the water surface. Changing the depth of the turbidity probe can change the ratio of coarse and fine particles sampled by both the turbidity probe and sampler intake.

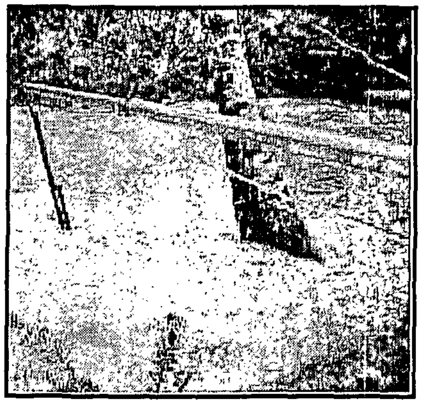

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Figure 4. The Freshwater boom with turbidity probe housing and intake submerged.

Pressure Transducer

The pressure transducer measures the head, or water pressure, at the sensor. The pressure transducer, a Druck 1830, is mounted below the lowest expected water stage. A vent tube inside the cable, open to the atmosphere where the cable terminates, compensates for changes in barometric pressure. The pressure transducer is calibrated before installation by submerging the sensor to known depths and recording the voltage signal. The data logger uses this relationship to convert the sensor's voltage readings to depth. It is possible, with the proper placement and orientation of the pressure transducer housing, coupled with averaging of multiple readings, to eliminate the need to dampen wave pressure with a stilling well.

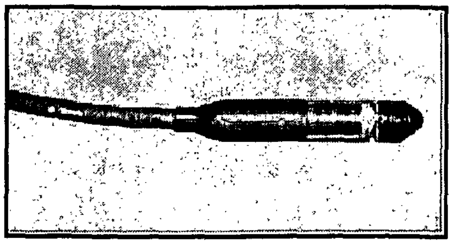

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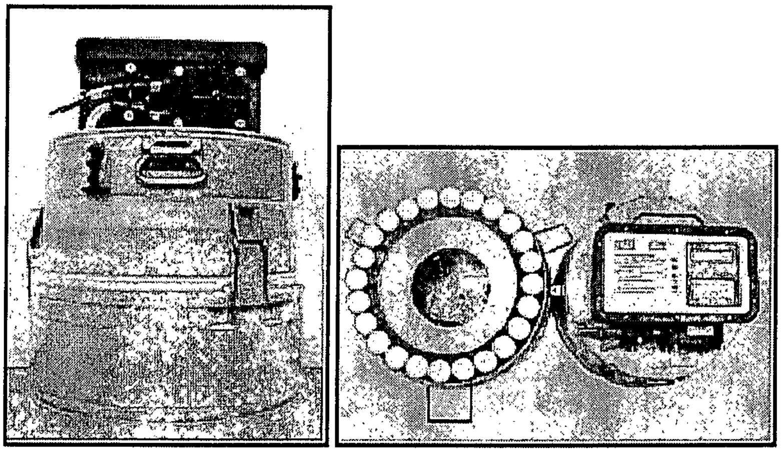
Figure 5. The Druck 1830 presure transducer measures stream head.

Automatic Water Sampler

Samples for laboratory analysis are collected with a 3700 Portable Sampler by Isco, Incorporated (ISCO). The intake tubing runs from the sampler's pump to within close proximity of the turbidity probe on the boom, Figures 6 and 7. Both the intake tubing and cable for the turbidity probe are routed inside the boom to provide protection.In some situations, locating the sampler intake and turbidity probe in different stream locations can increase the variability between the two measurements if the transported sediment is not adequately mixed. The pumping sampler is capable of collecting 24 samples under control of the TTS program. Sample volumes are set to approximately 350ml, or about 1/3 of available bottle volume. When the TTS program determines that all the rules have been met for collecting a threshold sample, the data logger triggers the ISCO sampler to collect one sample. The sampler's distributor arm then advances to the next empty bottle position and waits until the next signal from the data logger. Addition samples, via the TTS program, may be collected under control of field personnel to match depth-integrated manual samples or to increase the frequency of sampling under certain conditions. The bottles containing samples are removed for laboratory analysis at the same time that the data is transferred from the data logger. In situations where the transported sediment is predominantly coarse

(>0.5mm), and the required lift (head-height of the sampler above the stream) is more than approximately 10 feet, the line speed of the water sediment mixture in the intake tubing may be inadequate to capture a representative sample of large sediment particles. The particles' momentum may be too great for the sampler to reverse, or their settling rate may be too great, permitting them to fall out of suspension before reaching the sample bottle.



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Figures 6 and 7. Side and top views of the ISCO automatic water sampler.

TURBIDITY THRESHOLD SAMPLING FOR SUSPENDED SEDIMENT LOAD ESTIMATION

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Abstract: The paper discusses an automated procedure for measuring turbidity and sampling suspended sediment. The basic equipment consists of a programmable data logger, an in situ turbidimeter, a pumping sampler, and a stage-measuring device. The data logger program employs turbidity to govern sample collection during each transport event. Mounting configurations and housings for the turbidimeters have been prototyped and tested or deployed at 16 gaging sites in northwestern California. Operational data are presented with examples illustrating storm load estimation.

INTRODUCTION

The utility of information about suspended sediment transport is dependent on the timing and frequency of data collection. Even in seasonally snow-dominated watersheds, most of the annual suspended sediment is usually transported during a few, large rainstorm events. Automated data collection is essential to effectively capture such events. Although it is possible to rely solely on manual measurements, important storm flows are infrequent and difficult to predict, and when they do occur, trained personnel may not be available to collect the required information.

As of yet, there is no reliable method to directly measure total suspended sediment concentration (SSC) in the field. Pumped or manual samples must be transported to a laboratory for analysis. However, a number of manufacturers now offer turbidity sensors that can be deployed on a continuous basis in streams. While turbidity cannot replace SSC, it can be a tremendous asset as an auxiliary measurement. Turbidity can be used, along with discharge, in an automated system to make real-time sampling decisions linking turbidity to concentration. And the continuous turbidity record can reveal sediment pulses unrelated to discharge, providing information about the timing and magnitude of landslides or stream bank failures upstream.

METHODS

Sampling: The turbidity threshold sampling (TTS) method distributes sample collection over the range of rising and falling turbidity values and attempts to sample all significant turbidity peaks. A data logger records discharge and turbidity at frequent time intervals (10 or 15 minutes at current installations) and activates a pumping sampler when specified turbidity conditions are met. Discharge information is used to disable sampling when either the turbidity sensor or pumping sampler intake is not adequately submerged. The resulting set of TTS samples can be used to accurately determine suspended sediment loads by establishing a relation between sediment concentration and turbidity for any sampled period with significant sediment transport. The relation is then applied to the nearly continuous turbidity data.

Turbidity thresholds for sampling are based on the expected turbidity range for a given stream and the number of desired physical samples. The TTS method is designed to permit estimation of sediment loads for individual storm events that vary greatly in size. Thresholds are chosen such that their square-roots are evenly spaced (Lewis, 1996) to ensure the collection of samples during small events while holding the number of samples collected in large events within practical limits. Different sets of thresholds are used when turbidity is rising and falling, with more thresholds required during the lengthier falling period. To avoid oversampling due to transient turbidity spikes, each threshold condition must be met for two intervals before sampling is initiated and a minimum user-specified period of time must elapse before a sampled threshold can be re-utilized.

Reversals in turbidity are detected when the turbidity falls 20% below the previous maximum or 10% above the previous minimum, as long as the change is at least 5 NTU (nephelometric turbidity units). To avoid sampling during ephemeral turbidity reversals, the new direction must be maintained for at least two intervals. Upon reversal detection, a sample is collected if a threshold was passed between the actual time of the reversal and its detection. A pumped sample is collected when sampling is first enabled if the lowest turbidity threshold is exceeded, and pumped samples are collected at fixed intervals when the turbidity exceeds the upper limit of the turbidity sensor. In addition, field personnel can collect pumped samples, under program control, to pair with depth-integrated samples or to augment the number of threshold samples at any desired interval. A program is available from the authors to implement the sampling logic on Campbell data loggers. (The use of trade names is for information only and does not constitute endorsement by the U.S Department of Agriculture.) All of the numeric values in the algorithm are parameters that the user can easily change.

Suspended Sediment Load Estimation: Suspended sediment loads are ideally estimated for each storm using a turbidity sediment rating curve or *TTS rating curve*, which is a simple linear regression of SSC versus turbidity, based on the samples collected during the event being estimated. In a series of simulations (Lewis, 1996), the best or near-optimal results were obtained without data transformations or polynomial terms. The simulations were based on 10-minute records of turbidity and SSC that had been collected from five storm events at Caspar Creek in northwestern California. In some cases, more accurate estimates were obtained using quadratic regression, or separate regressions for periods of rising and falling turbidity. But the advantages were not large, and complex fitting procedures are best avoided, particularly with small samples, to limit extrapolation errors. Applying simple linear regressions resulted in root mean square errors between 1.9 and 7.7% for the five storms, with mean sample sizes between 4 and 11. These are very small errors by conventional standards of sediment load estimation.

The uncertainty of the load estimated from a TTS rating curve can be quantified using standard theory (Lewis, 1996). However, with small samples, the variance estimates themselves are subject to great uncertainty. In addition, if the model does not fit the population from which the data were sampled (difficult to assess from a small sample), the variance estimates can be very biased as well. In simulations where linear models were applied to nearly linear data with log-linear error distributions (Lewis, 1996), estimated standard errors of the load estimates exhibited root mean square errors from 38 to 72% of their true values, with bias up to 49%. Fortunately, the load estimates themselves exhibited root mean square errors of only 5.6 to 8.3% with a maximum bias of 4.0%.

At some gaging stations, we have found that there are often periods when the recorded turbidity is invalid, typically when the turbidimeter is not fully submerged or because debris or sediment are covering the sensor's optical window. Such conditions typically result in erratic turbidity readings that cause the algorithm to collect extra samples. If that is the case, it is usually not difficult to estimate the sediment load for the period of invalid turbidity using either time-interpolation or a sediment rating curve constructed from the extra samples. However, sometimes the pumping sampler's capacity (usually 24 bottles) is exceeded during a period of optical fouling, resulting in an un-sampled period. In these cases, unless the un-sampled period is very brief, the concentrations must be estimated using a sediment-rating curve constructed from a nearby period of time that covers the appropriate discharge range. The use of multiple estimation methods can result in discontinuities of the estimated concentration versus time. Sometimes discontinuities can be avoided by a judicious choice of methods or transition times between methods. The uncertainty can be judged in part by the amount that the load estimates change when different choices are made.

Equipment: The TTS method requires a data logger, a stage measurement device, a pumping sampler, a turbidimeter, a housing and mounting hardware for the turbidimeter, and a pumping sampler intake.

Data logger: The data logger records the stage and turbidity and signals a pumping sampler to collect a sample based on the TTS algorithm. The lack of a commercially available data logger, programmable in a high-level language, and available with the appropriate hardware interface to connect external devices, has been an impediment to the adoption of the TTS method. During water years 1996-1999, we utilized a TTS program written in TXBASIC, a dialect of the BASIC programming language that runs on ONSET Tattletale data loggers The practitioner must fabricate these data loggers from a single-board computer, a user-built interface board, and a memory board. Their fabrication and assembly proved to be an obstacle to the transfer of the TTS technology to practicing hydrologists. Therefore, in water year 2000 we converted the TXBASIC code to the widely available Campbell CR510 and CR10X programmable data loggers. The programming language and its capabilities are primitive but adequate and do permit us to distribute code that can immediately be used by hydrologists wanting to employ TTS.

Stage measurement: A device is needed that can provide the data logger with an electronic output linearly related to stage height. We have used pressure transducers at all our installations. The TTS program records the mean of 150 stage readings during each interval to increase the measurement precision.

Turbidimeter: *Our first experiments were with the Analite 190 turbidimeter (McVan Instruments, Co.).* Subsequently all of our gaging sites have deployed the OBS-3 turbidimeter (D&A Instruments, Co.). Both of these sensors are nephelometers that measure the scattering of infrared light and have a standard operating range of 0-2000 NTU. The TTS program records the median of 61 turbidity readings during a 30-second period to reduce the influence of outlier values.

Housing: Erroneous (usually inflated) turbidity readings can be caused by organics trapped on or near the sensor, entrainment of air bubbles, fine sediment or biological colonization of the optical window, or the proximity of the sensor to the water surface or channel bottom. Some turbidity sensors have been designed with electronically activated mechanical wipers or other devices to keep the optical window clean, but these have not gained wide acceptance due to reliability issues. In our experience, the most effective control of biofouling is through regular cleaning of the optical window, especially during periods of elevated stream temperature and solar input. But a properly designed sensor housing can limit most of the problems listed above as well as protecting the sensor from physical damage from large organic debris.

The sensor housing design is naturally dependent on the device being used. The OBS-3 that we have used at our gaging stations is cylindrically shaped and its optical window is positioned near the end and at a right angle to the probe's axis. We have found that enclosing the sensor in black ABS pipe, screened on the upstream end, created problems by reducing the velocity through the pipe, leading to regular coating of the optical window and pipe wall with a film of fine sediment during storm recessions. The most effective design we have tried to date encloses the sensor in a section of aluminum square tubing that is cut at a shallow angle on the downstream end to expose the optical window to the flow (Plate 1a). The sensor is oriented parallel to the flow with the optical window aimed sideways. In shallow streams, a solar visor is added above the optical window to reduce infrared saturation. This design effectively limits trapped organics and exposure of the detector to sun or water surface. And we have not experienced problems with fine sediment or air bubbles with this housing.

Mounting hardware: It is essential to mount the turbidity sensor and housing in such a way that it can be accessed at any time for cleaning. The mounting hardware should shed debris and keep the sensor above the bed load transport zone and below the water surface. In forested watersheds, it needs to protect the sensor from the impacts of large woody debris. Mounting configurations are very site specific. In the smallest channels, where flow depths rarely exceed 30 cm, we have mounted the turbidimeters on fixed brackets that are bolted to a plywood base staked into the channel. Brackets are drilled to mount the sensors at one of three heights. In channels that can be waded with flow depths up to 60 cm, we have mounted the turbidimeters on bottom-mounted floating booms (Plate 1b) or overhead suspension booms. On bottom-mounted booms the upstream end is hinged to the bed and the downstream end is fitted with a float, thus maintaining the turbidimeter at a depth proportional to the stage (Eads and Thomas, 1983). In larger channels, we have utilized bridge- or bank-mounted overhead booms (Plates 1c and 1d) that allow access to the sensor at any flow. Overhead booms are suspended vertically from a pivoting horizontal arm and typically are positioned and retrieved with a cable and winch system. The vertical arm is jointed to swing both downstream and sideways to shed large woody debris and to reduce stresses from changing flow lines.

Each of the boom configurations has advantages and disadvantages. Booms on fixed brackets are the simplest to build, but are suitable only for very small channels, where it may be impossible to keep the sensor submerged at all times. If the sensor is mounted too close to the bottom, bed load can bury the sensor or otherwise interfere with measurements during high flows. In small channels, the most promising approach seems to be overhead mounting in natural or artificially created pools. Booms hinged on the streambed have the advantage of keeping the sampling point at a constant proportion of the depth, but it is usually difficult to access the sensor for cleaning during high flows. In addition, bottom-mounted equipment is much more vulnerable than overhead-mounted equipment to damage by bed load. Overhead-mounted booms are the most difficult to build and install, but they allow access to the sensor at any flow. Their main disadvantage is that it is difficult to control the sampling depth. As flow increases the boom and sensor rise in the water column. Counter-weights are added to keep the sensor submerged at high flows, but the sensor's exact depth depends on frictional forces and is thus difficult to control.

Pumping sampler: At our gaging sites we have deployed ISCO pumping samplers, model 2700 or 3700, operated in a flow mode and activated by a signal from the data logger. The intake line from the sampler to the stream is

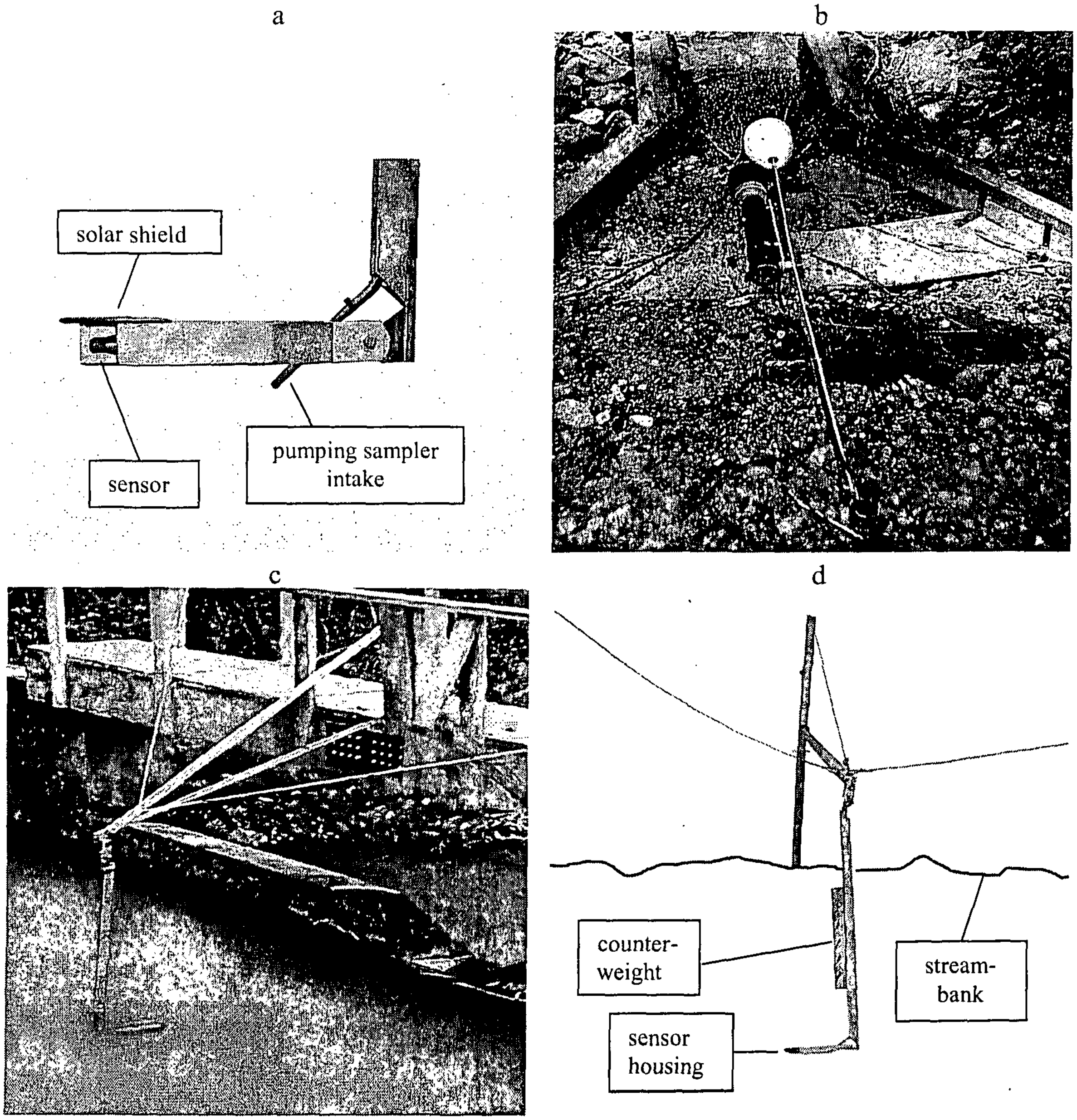

Plate 1. (a) Turbidity sensor in aluminum housing with solar shield, (b) bottom-mounted pivoting boom and sensor in ABS housing, (c) retractable bridge-mounted boom stabilized by lateral cables, and (d) retractable bank-mounted boom.

positioned so that it slopes continuously down to the intake nozzle, thus reducing the opportunity for sediment to fall out of suspension and become trapped. We use 0.635 cm inside diameter intake line to increase line velocity while ensuring representative sampling (standard line diameter is 0.953 cm). The intake is a stainless steel tube, of the same diameter as the intake line, and is often mounted on the boom in close proximity to the sensor. At some sites, the intake is mounted in a fixed position in the channel, at a height of 7.6 cm above the bed. In both mounting configurations the intake is positioned in the thalweg, pointing downstream (Winterstein, 1986).

Gaging sites: We have deployed in situ turbidimeters at 16 gaging stations in northwestern California. Some were used temporarily for testing purposes only. At three stations, both turbidity and SSC were collected at 10 or 15-minute intervals for pilot testing. One station was used briefly to test a new mounting configuration. The TTS program has been used to control sampling for at least one complete winter at 10 gaging stations. Twelve new gaging stations will be operational during the winter of 2000-2001.

Caspar Creek: Pilot testing was conducted in water years 1994 and 1995 at the 3.8-km^2 Arfstein station in the Caspar Creek Experimental Watershed near Fort Bragg, California. Caspar Creek is a sedimentary basin that produces mostly fine sediments. Turbidity and SSC were collected at 10-min intervals during 7 storm events. The data were subsequently used in sampling simulations to test the accuracy of TTS for estimating sediment loads (Lewis, 1996). Since water year 1996, the TTS method has been running on ONSET data loggers at 8 Caspar Creek gaging stations draining watersheds between 0.2 and 4.7 km^2. These stations are operated as part of a long-term research project focused on the hydrologic effects of forest practices (USDA Forest Service, 1998).

The two original Caspar Creek gaging stations are compound V-notch weirs. At these sites, the turbidity sensors are suspended in aluminum housings on retractable overhead booms mounted on bridges above the weir faces (Plate 1c). Another site has a bank-mounted overhead boom (Plate 1d) and one site has its boom suspended from a cable running across the channel. There are two sites with bottom-mounted pivoting booms (Plate 1b) and three sites have fixed mounts on the channel bed. In the winter of 2000-01, as part of a new study of third-growth logging, ten new gaging stations will utilize TTS in the 4.2-km^2 South Fork of Caspar Creek and its tributaries.

Other gaging sites: Turbidity and suspended sediment were collected at 15-minute intervals for two storms on Mill Creek, a boulder-bedded stream draining 63 km^2 of mostly dioritic terrain in the Hoopa Valley Indian Reservation. The bottom-mounted boom was destroyed and the turbidimeter lost when the streambed was entrained in a moderately high flow.

Our first experiment with an overhead boom (bank-mounted) was at Grass Valley Creek (80 km^2), which transports an abundance of coarse sandy material derived from decomposed granitic rocks. This location was a severe test for our equipment because of its coarse load, high velocities, woody debris loading, and freezing temperatures.

Upper Prairie Creek in Prairie Creek Redwoods State Park near Orick was an experimental site where a prototype bridge-mounted boom was deployed for one season. Bank-mounted booms have also been installed at Freshwater Creek (34 km^2), Little Jones Creek (71 km^2), Godwood Creek (4.4 km^2), and Horse Linto Creek (99 km^2) in Humboldt and Del Norte Counties. Freshwater Creek was the first site where TTS was implemented on a Campbell data logger. The program has been running for two winters there, and for a partial season at Little Jones Creek. Godwood Creek and Horse Linto Creek have no pumping samplers and are collecting only turbidity data.

RESULTS AND DISCUSSION

The most successful installations have been at sites with overhead booms using the aluminum housing design. At these sites, the sensor is continually submerged, interference from debris is minimized, and the sensor can be accessed at any time for cleaning.

Two examples from Caspar Creek (Figure 1a, b) demonstrate the utility of TTS in situations where discharge-sediment rating curves would have failed to adequately describe supply-limited sediment transport. The first case, from the South Fork weir, was a double-peaked storm in which the second discharge peak was higher than the first, while the relative magnitudes of the turbidity peaks were reversed. The second case, from the Dollard tributary, shows two sediment peaks completely unrelated to discharge. We know the sediment originated from the channel in the 600-meter reach between Dollard and the upstream Eagle gaging station because (1) no turbidity spikes occurred at Eagle, and (2) the only active erosion sources in that reach are the channel banks and bed. In both examples, there was a tidy linear relation between laboratory SSC and field turbidity, dispelling any doubt that might exist about the veracity of the turbidity spikes. The coefficients of variation (standard error divided by estimated suspended load) in these two examples were 2.3% and 10.2%, respectively.

A single TTS rating curve is not always entirely satisfactory for defining the sediment transport during a storm event. The predicted concentrations at low turbidities during the storm recession are commonly too low or even negative. In a typical example from Freshwater Creek (Figure 1c), this was easily remedied by applying a second

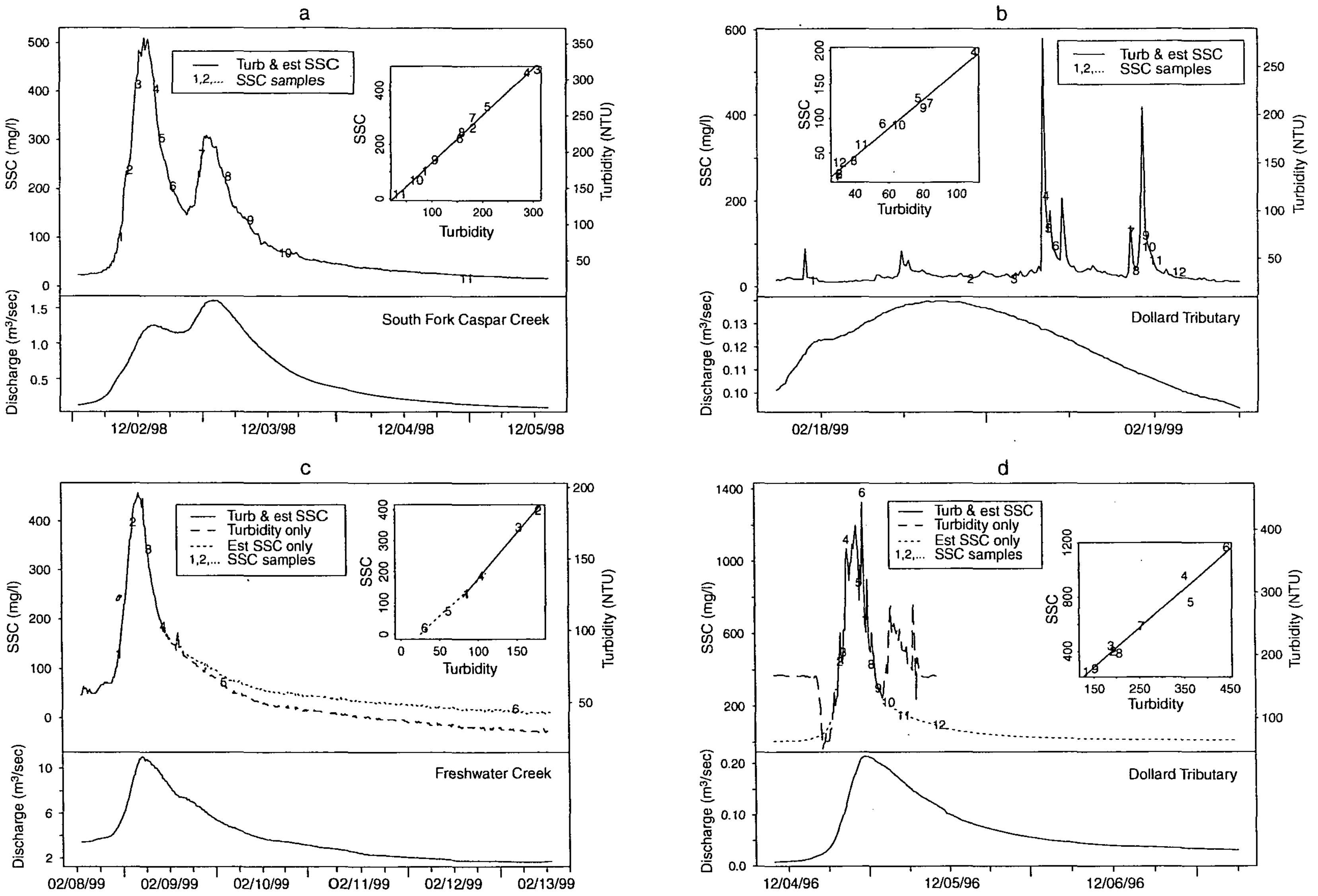

Figure 1. Suspended sediment concentration (SSC), turbidity, and discharge in four storm events. Inset graphs show TTS rating curves used to estimate SSC. Plotted numbers represent measured SSC. Solid lines in upper frames of (a), (b), (c), and (d) represent both turbidity and SSC estimated from TTS rating curve. Left-hand SSC axis is scaled to right-hand turbidity axis through the TTS rating curve. Dashed lines in (c) and (d) represent turbidity only. Dotted lines show SSC estimated from a second TTS rating curve (c) or from discharge-based rating curves (d).

TTS rating curve, based on the last three samples, for the recession period. The load estimated from the two rating curves, each based on three samples, is only 2% greater than that from a single rating curve (replacing negative predictions with zeroes), but the predictions from the second rating curve are clearly more realistic for the recession.

Negative predictions on storm recessions might in some cases result from using 1-micron filters in the laboratory. In 1-micron filtrate from 65 samples collected at 8 of the Caspar Creek gaging stations, an average of 15.5 mg/l was measured on 0.22-micron membrane filters. Assuming the relation between total SSC and turbidity passes through the origin, the effect of disregarding the finest particles is to shift the TTS rating curve downward, creating a negative y-intercept. Extrapolations at the low end of the regression thus can result in negative predictions of concentration.

Various problems often preclude using a TTS rating curve for much of the storm. Figure 1d shows a storm at the Dollard station in 1996, before the turbidimeter was relocated to a pool. In the first part of the storm, the turbidimeter was not submerged because the water was too shallow. Beginning early on Dec. 5, the sensor became fouled with debris. Several hours later, the field crew removed the debris, but made an error that resulted in no electronic data or samples being collected for the remainder of the storm. The discharge for the missing period was later reconstructed from the Eagle station upstream and SSC was estimated for the start and end of the storm using two sediment rating curves. The relation of SSC to discharge formed a wide hysteresis loop, but the first four samples and final three samples of the loop defined more-or-less linear relationships. Therefore separate sediment rating curves were computed from these two subsamples and applied to the periods of invalid or missing turbidity at each end of the storm.

Sometimes when the sensor is fouled, fluctuations in turbidity are produced that result in collection of enough additional samples to adequately define the temporal trend in SSC without resorting to a sediment-rating curve. In these circumstances, linear interpolation between the measured values of SSC is all that is necessary to reliably estimate the load during the period of missing turbidity.

Sampling at Mill Creek and Grass Valley Creek was conducted in order to investigate the feasibility of the TTS method where suspended particles are mostly sand. In the storms sampled at Mill Creek, about half the load consisted of sand, but most was fine sand less than 0.5mm. The TTS rating curve for the larger of the two storms (Figure 2) suggests that the TTS method should work fine in this stream. Whereas the bottom-mounted boom was destroyed at Mill Creek, the prototype overhead boom at Grass Valley Creek was able to withstand impacts from large woody debris transported at velocities as high as 15 ft s^{-1}. However, at Grass Valley Creek, the load was so coarse and the velocities often so great that in one storm the concentration of particles larger than 0.5mm in pumped samples averaged just 4% of that in simultaneous depth-integrated samples (*n*=8). The relations between SSC from pumped and depth-integrated samples (composited from multiple verticals) are shown in Figure 3. These relations indicate that, unless a pumping sampler becomes available that can efficiently sample sand-size particles at both

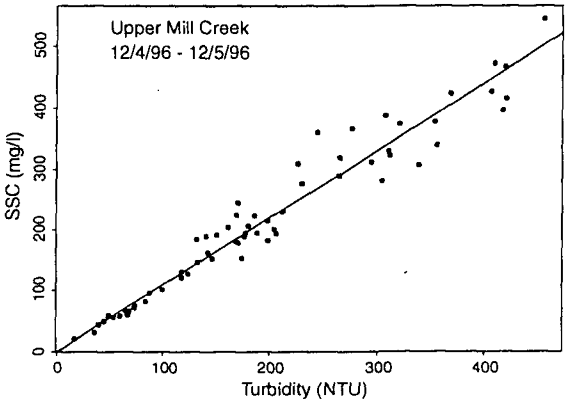

Figure 2. TTS rating curve (regression line) based on a fixed 15-minute sampling interval at Upper Mill Creek

high velocities and moderate head heights, the TTS methodology can be effective at estimating only the finest part of the load in streams such as Grass Valley Creek. Unless a tight and reliable relationship could be established between pumped and manual SSC, manual samples would be required throughout high transport events to reliably estimate the total suspended load.

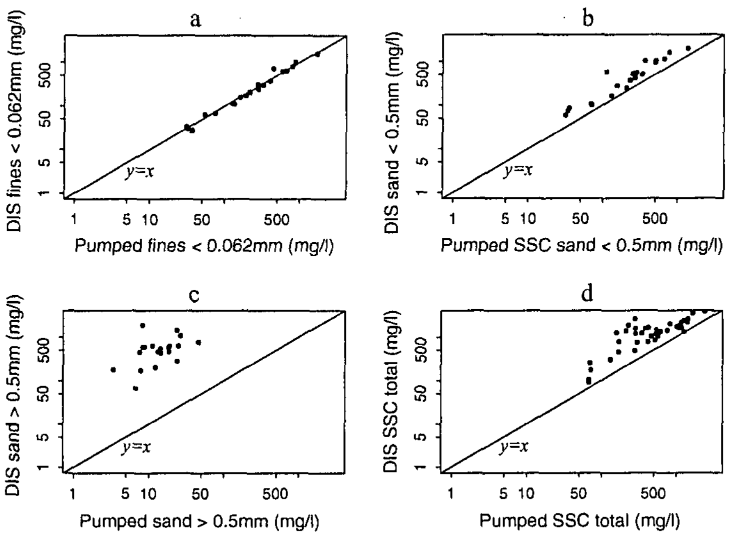

Figure 3. Comparison of SSC in 1998 at Grass Valley Creek from depth-integrated D-49 samples and simultaneous pumped samples for (a) fines < 0.062mm, (b) fine sand < 0.5mm, (c) coarse sand > 0.5mm, and (d) all particles.

The TTS method can also be used to estimate seasonal or annual sediment loads, either by summing storm event loads or by applying seasonal or annual TTS rating curves. However, since TTS samples every significant sediment pulse, it probably collects more samples than necessary for the task. A more suitable approach, when event loads are not of interest, might be random sampling stratified by turbidity. Such a design should be an improvement upon the similar flow-stratified sampling method, which Thomas and Lewis (1995) recommended for estimating seasonal and annual loads.

CONCLUSIONS

Turbidity Threshold Sampling is a proven method for accurately measuring suspended sediment loads at stream gaging stations on a storm event basis. If turbidimeters are properly installed and maintained, the sampling algorithm distributes samples over the entire turbidity range during each transport event. However, in streams with very coarse suspended loads, accuracy is limited by the ability of pumping samplers to collect representative samples.

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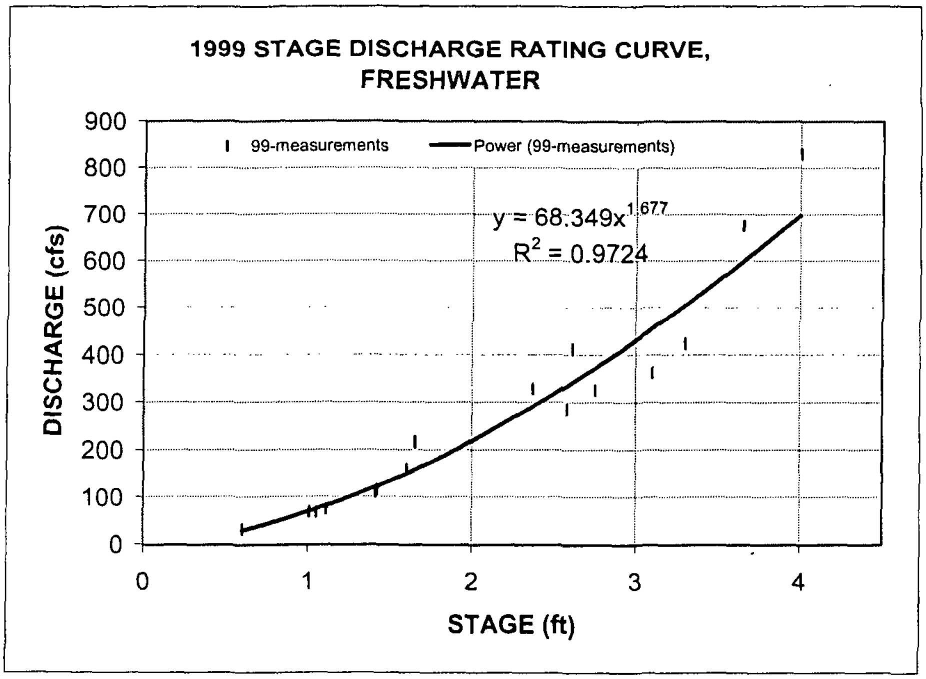
1999 Measurements

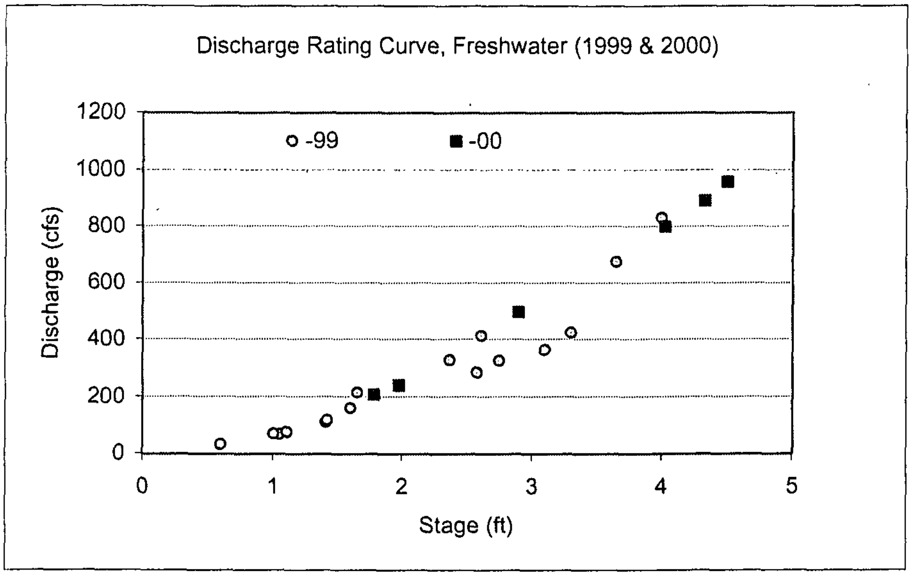
DATE	TIME	QUALITY	AVERAGE STAGE (ft)	DISCHARGE (cfs)
12/17/98	1545	good	0.6	31.37
1/16/99	1635	good	1.05	67.09
1/19/99	1300	fair	1.6	160.18
1/23/99	1116	good	2.37	328.38
1/24/99	1000	good	1.41	109.8
2/6/99	921	poor	1.11	74.25
2/6/99	1009	poor	1.65	215.46
2/6/99	1054	poor	2.61	413.01
2/6/99	1150	poor	3.65	674.87
2/6/99	1306	fair	4	831
2/6/99	1524	good	3.3	423.7
2/6/99	1602	good	3.1	363.17
2/6/99	1701	fair	2.75	325.92
2/6/99	1758	fair	2.58	285.34
2/8/99	1556	good	1.42	116.5
2/15/99	905	good	1.005	68.6

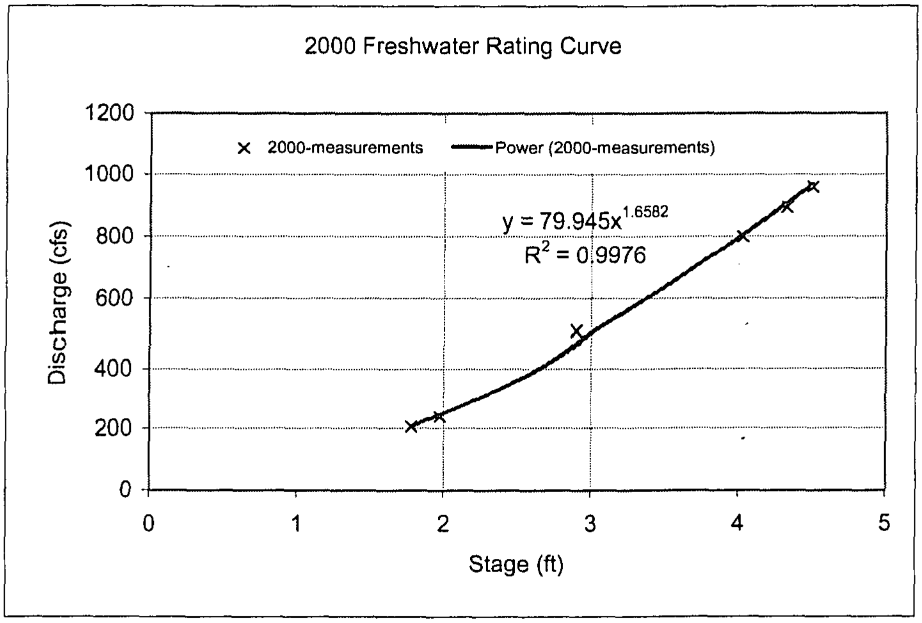
2000 Measurements

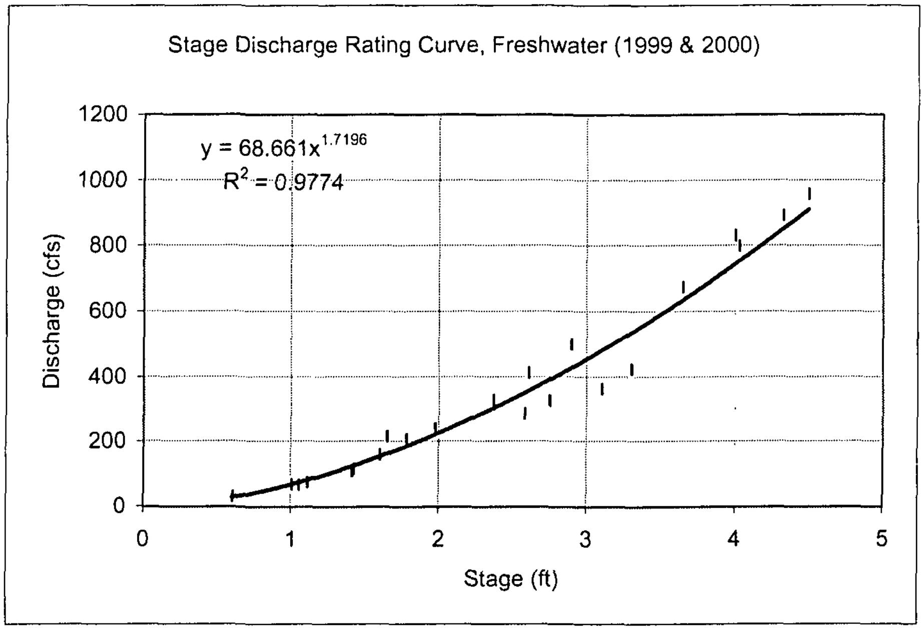
DATE	TIME	QUALITY	AVERAGE STAGE (ft)	DISCHARGE (cfs)
1/14/00	1115	good	4.325	891.9
1/14/00	1031	good	4.5	958.5
1/14/00	1627	good	2.9	498.9
1/14/00	1235	good	4.025	799.5
1/11/00	2113	good	1.78	207.3
1/11/00	1740	good	1.975	239.9



1999 STAGE DISCHARGE RATING CURVE, FRESHWATER


Discharge Rating Curve, Freshwater (1999 & 2000)
○ -99
■ -00
Discharge (cfs)
0
200
400
600
800
1000
1200
Stage (ft)
0
1
2
3
4
5


2000 Freshwater Rating Curve
× 2000-measurements
Power (2000-measurements)
y = 79.945x^1.6582
R^2 = 0.9976
Discharge (cfs)
0
200
400
600
800
1000
1200
Stage (ft)
0
1
2
3
4
5


Stage Discharge Rating Curve, Freshwater (1999 & 2000)
y = 68.661x^1.7196
R^2 = 0.9774
Discharge (cfs)
1200
1000
800
600
400
200
0
0
1
2
3
4
5
Stage (ft)

RSL PubSearch Results

The following publications contain references to **turbid**: (9 total)

- **Publications by Watershed Scientists:**
    - **FY2001 Publications & Manuscripts:**

        Lewis, Jack, and Rand Eads. In press. Turbidity threshold sampling for suspended sediment load estimation. *In:* Proceedings, 7th Federal Interagency Sedimentation Conference, 25-29 Mar 2001, Reno, Nevada. *[1824 KB]*

    - **Published between 1990 and 2000:**

        Barber, Teri J. 1996. Hetten and Tompkins paired watershed study: turbidity and SSC from paired managed and unmanaged watersheds. Watershed Management Council Networker 6(4): 8-10.

        Barber, Teri Jo. 1997. The Hetten and Tompkins creeks paired catchment study: modern U. S. Forest Service timber harvest effects on suspended sediment concentration and turbidity. M.S. Thesis, Humboldt State University, Arcata, California. 232 p.

        Lewis, Jack. 1996. Turbidity-controlled suspended sediment sampling for runoff-event load estimation. Water Resources Research 32(7): 2299-2310. [Caspar Creek]

        Lewis, Jack, and Rand Eads. 1996. Turbidity-controlled suspended sediment sampling. Watershed Management Council Newsletter 6(4): 1&4-5. [Caspar Creek]

        Lewis, Jack, and Rand Eads. 1998. Automatic real-time control of suspended sediment based upon high frequency *in situ* measurements of nephelometric turbidity. *In:* Gray, John, and Larry Schmidt (Organizers). Proceedings of the Federal Interagency Workshop on Sediment Technology for the 21st Century, February 17-20, 1998, St. Petersburg, FL.

        Lewis, Jack, Rand Eads, and Noah Campbell-Lund. 2000. Turbidity threshold sampling program (TTS). Software release TTS_3_0.csi. USDA Forest Service, Redwood Sciences Laboratory, Arcata, California. March 2000. 57 p. PDF file or Campbell source code as text

        Reid, L. M. 1998. Forest roads, chronic turbidity, and salmon. EOS, Transactions, American Geophysical Union 79(45): F285. *[3 KB]*

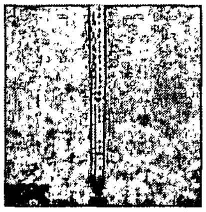
    - **Published before 1990:**

        Markman, S. G. 1989. Longitudinal variation in suspended sediment and turbidity of two undisturbed streams in northwestern California in relation to the monitoring of water quality above and below a land disturbance. M.S. thesis. Humboldt State University, Arcata, California. 62 p.

- **Publications by Wildlife Scientists:**
    - **FY2001 Publications & Manuscripts:**

Freshwater Creek, California...

Freshwater Creek Hydrologic 1999 Data Definitions



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ftr99_15min.txt

Contents: 1 record every 15 minutes 1/13/1999:1800 through 8/1/1999:0000

date	Date (mm/dd/yy)
time	Military time (00:00 - 24:00)
dump	Batch number
bottle	Bottle number (1-24)
stg	Stage (water height) in feet
stgcode	Stage code[1]
discharge	Water discharge (cubic feet per second
turb	Turbidity (NTU)
turbcode	Turbidity code[2]
estssc	Estimated[3] sediment concentration (mg/l)
wtemp	Water temperature (degrees Celsius)
rain	Rainfall (inches)

ftr99_sed.txt

Contents: 1 record for each pumped sediment sample

date	Date (mm/dd/yy)
time	Military time (00:00 - 24:00)
dump	Batch number
bottle	Bottle number (1-24)
stg	Stage (water height) in feet
stgcode	Stage code[1]
discharge	Water discharge (cubic feet per second
turb	Turbidity (NTU)
turbcode	Turbidity code[2]
ssc	Laboratory sediment concentration (mg/l)

[1] Stage code:

0 = good
1 = adjusted (to agree with observer staff plate readings)
2 = interpolated; good
3 = interpolated; fair
4 = interpolated; poor

[2] Turbidity code:
0 = good
1 = adjusted
2 = interpolated; good
3 = interpolated; fair
4 = interpolated; poor

[3] HY 1999 Estimated sediment concentration was computed from a **loess (locally weighted) regression** of turbidity versus laboratory sediment concentration, based on all lab samples from hydrologic year 1999. HY 2000 Estimated Sediment concentration was computed from a **linear regression** of Turbidity versus laboratory sediment concentration, based on all lab samples from hydrologic year 2000.

| Turbidity Threshold Publications | Back to Main Page |
- Salmon Forever - Redwood Community Action Agency - Redwood Sciences Lab -

Freshwater // Last updated on October 24, 2000, by Ben Bray