Turbidity and Suspended Sediment Measurements Using OBS Meters, West Arm Demonstration Forest Sediment Budget Study

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TURBIDITY AND SUSPENDED SEDIMENT MEASUREMENTS USING OBS METERS, WEST ARM DEMONSTRATION FOREST SEDIMENT BUDGET STUDY

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Abstract: We have completed 3 years of turbidity and suspended sediment measurements as part of a sediment budget study in community watersheds near Nelson, B.C. The OBS (optical back-scatter) meter has been an important tool. This paper will briefly review some of the results of this study, as they relate to water quality and forest development. More importantly, it will discuss some of the practical aspects of instrumentation and sampling.

Our measurement sites are located on creeks which are not especially subject to severe floods or debris movement, and are in an easily accessible populated area close to our headquarters. Despite these advantages, we have experienced a certain amount of lost data, mostly due to battery failure, and to fouling of sensors by natural processes. Under conditions of low turbidity, the zero of the OBS meters has been found to fluctuate by up to 5 NTU from the lab-calibrated zero. Large erroneous readings are caused by algae growth, bubbles in rapid flow, bedload accumulation, vegetative debris, and sunlight. We have found the OBS measurements to be very useful for continuous measurement of turbidity, but they are of almost no value unless they are combined with a program of manual water sampling, and frequent field servicing by a skilled technician. It is feasible to use OBS measurements to estimate suspended sediment yield, but the regression relation is sensitive to grain size distribution and is unique for each watershed.

Introduction

Water quality monitoring, especially measurement of turbidity and suspended sediment concentration, is being conducted on an increasingly routine basis in forest land in B.C. This is driven mainly by the introduction of the Forest Practices Code in 1995, which requires that forest operations be conducted so as to protect water quality in streams which are used for community water supply or which are used by fish. This paper gives a brief review of preliminary results of a sediment monitoring project in the West Kootenays, and discusses some practical aspects of turbidity and suspended sediment measurement.

The West Arm Demonstration Forest sediment budget study

Land use in watersheds used for community water supply in the West Kootenays is a complex and contentious problem. The amount of sediment in water is one of the main issues. Quantitative data on sediment yields of watersheds, and on the effects of forest development on sediment yields, are required in order that land use disputes can be resolved in an intelligent manner. To meet this need, a sediment budget project was started in 1992 in the West Arm Demonstration Forest near Nelson (Figure 1).

The objectives of the project are:

- to identify natural and development-related sources of sediment in typical watersheds which are used for community water supply;
- to investigate the effects of road construction, maintenance, and deactivation, and of different silvicultural systems, on sediment production;

- to investigate the physical processes by which sediment is delivered to the channel system, stored in channels, and discharged at the stream outlet; and
- to investigate precipitation and snowmelt events which are significant in sediment production.

Two watersheds are being monitored: Redfish Creek, which has an extensive road network and has experienced logging over the past 30 years, and Laird Creek, which is undeveloped and acts as a control. The two watersheds have similar physiographic and hydrologic characteristics, and drain areas of 26 and 15 km^2 respectively. Both creeks are heavily used for domestic water supply, and Redfish Creek has a Kokanee salmon spawning channel at its mouth. Streamflow, turbidity, and suspended sediment concentration are measured near the outlet of each creek; and sediment sources are monitored at a number of locations in the watershed of Redfish Creek.

The study is being conducted in cooperation with researchers of the Canadian Forest Service, who measures soil erosion and sediment sources in the Redfish watershed, and with the Water Survey of Canada, which operates gauging stations on the two creeks. The project is expected to last for about 10 years. Three years of data have been collected to date.

A sediment budget approach requires quantification of the sources of sediment, changes in sediment storage in the stream channel network, and sediment discharge at the stream outlet. This can be expressed as an equation:

$$I = O + \Delta S$$

where I is input, O is output, and ΔS is change in storage. The equation can be applied at any scale of interest, from an entire watershed to a single reach of stream channel. In practice, the equation is often applied separately to suspended sediment (fine sand, silt, and clay), and bedload (coarse sand and gravel), since the physics of transport and storage of the two types of sediment are very different.

This paper focuses on some of the results and measurement problems of the suspended sediment component of the study. The use of OBS (optical back-scatter) meters for continuous measurement of turbidity is an important component of the study. Turbidity is a surrogate measurement for suspended sediment concentration, and is itself a variable of interest for water quality.

Some preliminary results of the study

A very brief summary of results from the first two full years of the study is given here. They are based on turbidity measurements from OBS meters at the gauging stations near the creek mouths, daily sediment samples collected during the spring freshet each year, and observations of sediment sources in the Redfish Creek watershed. A more detailed discussion of the results, and the methods used in computation of sediment volumes, will be given in an internal Ministry of Forests research paper now in preparation.

A nearly continuous record of turbidity was collected during the spring and summer of 1993 and 1994, for both Redfish and Laird Creeks at the Water Survey of Canada gauges near the creek mouths. This record is in the form of average turbidity for 15-minute periods throughout the day. Figure 2 shows the 1993 data for Redfish Creek, along with the turbidities of the daily water samples. For Redfish Creek in 1993, the sediment yield was computed from the turbidity record by transforming this into a record of calculated suspended sediment concentration, using a regression relation (see next section). The concentration is then multiplied by stream discharge to give suspended sediment yield. (As Table 2 shows, this gives a similar result to computing suspended sediment yield directly from the sediment concentration of the daily water samples). On Laird Creek for both years, most of the data at high discharges was erroneous due to the effect of bubbles in the water, and the record for Redfish Creek in 1994 had some missing data during the peak discharge period for unknown reasons. Therefore, the sediment yield was computed from the daily samples alone.

Table 1 summarizes the sediment yield calculations, for the spring freshet period (May 1 to June 9, 1993, and April 21 to June 19, 1994). Sediment yield during the remainder of the year was relatively insignificant, so it is not included in this analysis. These results show that for both years, the sediment yield per unit area for Redfish Creek was about double that for Laird Creek.

At several sites in the Redfish Creek watershed, sediment traps were placed in gullies, on small tributaries, and below road culverts. Observations were also made following the spring freshet and summer rainstorms of sites of measurable erosion along roads. The total observed sediment production at these sites is noted in Table 1. The suspended sediment component is estimated to be 25% of the total eroded sediment, based on grain-size analysis of the sediment sources. Although the largest discrete sediment sources were included in this inventory, numerous smaller sources were unmeasured, and there were also distributed sources of erosion from road surfaces and ditches which were observed but which could not be readily measured. Therefore, it is suspected that sediment production from roads was several times as great as shown by the numbers in the table. Soil erosion was also monitored in a recently logged clearcut, and casual observations were made at several older cutblocks. Sediment production from these sites was negligible compared with sediment production from roads.

From the preliminary results obtained to date, about one-quarter to one-half of the "extra" suspended sediment produced in the Redfish Creek watershed (that is, the amount in excess of the unit area sediment yield in the undeveloped Laird Creek watershed) can be accounted for by measured erosion from logging roads. The remaining sediment may be due to other development-related sources which were not measured, or to natural sources (which may be different in the two watersheds).

It should be noted that the suspended sediment yields measured here are quite low compared with most of those measured elsewhere in British Columbia. Yields reported by Church et al. (1989) for small non-glacierized watersheds range from about 3 to 70 Tonnes/km^2/year, and from about 44 to 470 for many larger rivers. The low yield of Redfish and Laird Creeks reflects the granitic bedrock and the relatively low level of geomorphic activity in the area. These creeks, like many similar ones, are used for community water supply at least in part because they have high water quality and low suspended sediment yields, compared to alternative sources.

Methodology of measuring suspended sediment yield

Several possible approaches to measuring suspended sediment yield at the outlet of a watershed are possible. These include:

a. Collect daily sediment samples, and assume the sediment concentration of each sample is representative of the entire day.
b. Collect daily or miscellaneous sediment samples, and derive a discharge-concentration rating curve.
c. Collect frequent (e.g. hourly) sediment samples using an automatic pump sampler.
d. Measure turbidity continuously, and derive a turbidity-concentration relation from sediment samples taken concurrently. Calculate suspended sediment yield from this relation.

Option (a) is the simplest. However, it has a major problem in that sediment concentration varies greatly throughout the day, often in a systematic manner (e.g. peaking at about the same time each day during the spring freshet). The results of this approach are likely to be biased, if samples are regularly taken at a similar time each day. In the summer and fall, sediment production takes place during rainstorms which are often of short duration, so daily samples are likely to miss the events. Option (b) appears to avoid some of these problems; however, discharge-concentration relations are highly subject to hysteresis, so the results are likely to be inaccurate. Option (c) is prohibitively expensive for most applications, but may be a useful technique combined with other approaches, if an automatic sampler can be programmed to operate only during peak events. Option (d) has advantages of a continuous data record and reasonable economy; however, it relies on a precise turbidity-concentration relation.

In this study, option (d) was chosen, combined with option (a) for deriving the turbidity-concentration relation, and as a backup against missing data.

The instrumentation used at the main sites, located at the Water Survey of Canada (WSC) gauging stations, consists of a D&A Instrument Co OBS-3 turbidity meter, a Sensotec LL-V pressure transducer, and a thermistor probe, connected to a Campbell Scientific CR10 data logger. The OBS meter is mounted to a piece of angle iron attached to the steel culvert used as the stilling well, and is placed so as to be sheltered by the culvert to avoid mechanical damage from debris carried by the creek. The pressure transducer is redundant at these sites, as water level is also measured by the WSC's chart recorder. At other sites on small tributaries of Redfish Creek, a plywood V-notch weir is used to measure discharge, and the OBS meter and pressure transducer are attached to the upstream face of the weir.

The data recorded are mean turbidity and water level for 15-minute periods, and daily mean and daily maximum and minimum instantaneous values. The choice of a 15-minute time period was a compromise between data logger storage capacity, and the desire for a nearly continuous record. The OBS meter is operated continuously, which places a considerable demand on the batteries since it has the greatest power requirement of the instruments used (it draws about 14 mA at 12 V). Various 12 V batteries are used, most commonly a recreational vehicle type lead-acid automotive battery. We have not used solar panels, as the sites are in dense forest and receive little direct solar radiation.

Water samples are collected by a local resident, daily from about April 15 to June 15, and weekly at other times. Samples are normally taken in the afternoon. We attempt to have samples collected during summer rainstorm runoff events, but this is not often successful because the events are usually of short duration and cannot be forecasted. The samples are taken at sites about 1 km downstream from the instrument sites for reasons of economy, since the sites themselves are not road accessible. They are grab samples taken from the bank; since the creeks are steep and bouldery with tumbling flow, this method probably gives results which are equivalent to depth-integrated samples. We also service the instrument sites at one to two week intervals, to clean the OBS meters, check for obstructing debris, and check the batteries. Additional samples are taken at these visits.

The process of calculating suspended sediment yield from the OBS meter data includes the following steps:

1. The OBS meters are calibrated in our lab with formazin.
2. The data from the OBS meters are processed to provide a record, at 15-minute intervals, of apparent turbidity. As part of this step, missing data must be either estimated by interpolation (for short gaps) or left as a gap. Also, the record is examined for spurious data, which is rejected. This step is laborious, and requires skill and judgment.
3. The turbidity of each water sample is measured in the lab using a Hach turbidity meter.
4. The OBS turbidity record is compared to the turbidities of samples taken at the same time. Usually when the turbidity of the water is low, the apparent OBS reading is higher than the sample turbidity. A zero correction is determined and is applied to the data. This step also requires judgment, as it is quite subjective, and we have not been able to devise an automated or an objective method of doing it. One problem is the OBS value is a 15-minute average, and may not coincide with the turbidity at the time the sample was taken, since the turbidity can vary over a shorter time scale than 15 minutes. Also the usual sample site is some distance downstream from the instrument site, and there may be discrepancies due to travel time of the water or to sediment sources between the two points.
5. Selected water samples are sent to a lab (currently the Water Survey of Canada lab in Regina) for suspended sediment analysis. The selected samples include all those with turbidity greater than 1 NTU, and a small proportion of lower turbidity samples.
6. The data from these samples are used to derive a regression relation between turbidity and suspended sediment concentration. This is used to calculate suspended sediment concentration from the OBS turbidity record.
7. The calculated sediment concentration is then multiplied by stream discharge, to give a "continuous" (15-minute) record of suspended sediment discharge. The calculated daily sediment discharge is the sum of the 15-minute values.
8. For days with missing turbidity data, the suspended sediment concentration from the daily sample is used to estimate the sediment yield, using option (a) which assumes that the sample is representative of the entire day.

Each step in this procedure has the potential for errors, some of them quite large and difficult to quantify. Some idea of the errors involved can be obtained by comparing sediment yields calculated by several different methods.

Figure 3 shows the calculated suspended sediment concentration, along with stream discharge, for Redfish Creek during the 1993 spring freshet. The curve is derived from the one shown in Figure 2 by correcting the turbidity zero, and then applying the regression relation between turbidity and sediment concentration, as described above. Figure 4 shows daily suspended sediment yield calculated by three methods: from the sum of this "continuous" data; from multiplying the daily mean sediment concentration, derived from the corrected daily mean turbidity, by the daily mean discharge; and from the sediment concentration of the daily sample. Table 2 shows the total sediment yield for the freshet period calculated by these three methods.

The sediment yields calculated from the "continuous" turbidity record are consistently slightly higher than those calculated from the daily means. This is to be expected, since the sediment yield is the product of two quantities which are positively correlated; the values calculated from daily means are therefore negatively biased. The yields calculated from the daily sediment samples show great variability from day to day, when compared to the yields calculated from turbidity, depending on whether or not the sample happened to coincide with the time of daily maximum turbidity. However, the total yield for the season is surprisingly close to that calculated from turbidity; apparently, the daily variability is sufficiently random that it tends to cancel out over many days. This may be fortuitous, as the samples were not taken at random times, but were deliberately collected in the afternoon when the creek level is likely to be high. However, it lends some confidence to seasonal sediment yields that include values estimated from the daily sediment samples, when turbidity data was missing.

Figure 5 shows the regression relation between turbidity and suspended sediment concentration for samples collected on Redfish Creek in 1993. A large number of samples which had concentrations of 0 mg/l are not shown. The data are obviously clustered at low turbidity and suspended sediment values. For calculating the regression relation, only points for which the sediment concentration was greater than 2 mg/l were used. The regression line is curved because (turbidity - 0.25) was used as the independent variable; this is because the turbidity of distilled water (as measured by our turbidity meter) is 0.25 NTU, and a sample of creek water containing 0 mg/l of sediment cannot have a turbidity less than this. The relation is apparently quite inaccurate at the low end; however, this has relatively little importance for calculating the seasonal sediment yield, since most of the sediment transport occurs on a small number of days when both sediment concentration and discharge are high.

Errors in the lab measurements of turbidity and sediment concentration may be responsible for much of the variability at the low end of the curve. Otherwise, the variability in the relation between turbidity and suspended sediment concentration is probably due to variation in sediment composition. Organic material is visibly abundant in turbid water on these creeks, especially early in the season. A high concentration of organic material results in high turbidity for a relatively low weight (in mg/l). Since these creeks drain a granitic source area, there is a high proportion of sand in the suspended sediment as compared to silt and clay. A higher sand content gives a high weight for a relatively low turbidity. The composition of the sediment is likely to vary depending on which source areas are responsible for the sediment yield on a particular day. Sources high in organic material include streamside accumulations of rotting leaves and other forest litter, picked up by the rising creek early in the spring, erosion of surface soil horizons, and snow avalanche deposits. Sources which may be high in coarse-textured mineral material include erosion of subsurface soil (especially road and ditch erosion), bank erosion, debris flows, and remobilization of sand bars deposited during previous low water.

A strong hysteresis effect was observed for both continuous and daily mean sediment concentrations, if these are plotted against discharge. Relatively higher sediment concentrations occur early in the season on the rising limb of the spring freshet, and on the rising limb of each daily hydrograph. For this reason, it is not reasonable to use a simple rating curve between discharge and sediment concentration.

Problems and errors associated with turbidity measurements

In addition to the errors involved in calculating suspended sediment yield from turbidity described above, there are considerable errors and practical difficulties associated with the turbidity measurements themselves. Some of these are described here.

One of the most serious problems, in terms of lost or inaccurate data, is fouling of the OBS meters. Over time, the OBS sensor can accumulate a thin layer of a pollutant which is probably algae, scum, or fine sediment. This results in erroneous high turbidity readings. The only way we have found to deal with this problem is by frequent maintenance visits to the site to clean the instrument. Figure 2 shows an extreme example: if we had not happened to make a maintenance visit just before the rise in the hydrograph, the entire spring freshet's data would have been lost. During low water in mid to late summer, when the water is warm, algae growth appears to occur frequently. This often shows up as a gradual linear increase in apparent turbidity, followed by an abrupt drop, probably as the stream current pulls off the growing algae filaments. Figure 6 shows examples of this behaviour. Even when clean, the output of the OBS meter at close to zero turbidity is almost always higher than the zero measured during lab calibration. In the field, this zero varies, apparently randomly, over a range of up to several NTU. This variability may be partly due to temperature fluctuations, or to changes in the state of cleanliness of the sensor.

Data can also be lost when objects such as leaves or twigs lodge against the sensor. This often happens during high water in the spring. Sometimes large branches snag on the bank or on parts of the instrument site, and cause erroneous high readings if part of the branch is in the light beam of the OBS meter. Frequent inspection and cleaning is the only way to minimize this problem.

In highly turbulent flow, bubbles entrained in the flow can cause erroneous high readings. At the two sites at the Water Survey of Canada stations, we positioned the OBS meters in the relatively sheltered pool behind the stilling well, to minimize this problem. However, on Laird Creek, which flows in a continuously steep, bouldery channel, and we could not find a location near the station where bubble-filled water was not a problem. As a result, most of the data at high discharges was useless. In 1995 and subsequent years, we are using a second temporary instrument site for the high-flow period, as we have been unable to find a site which appears suitable for both high and low flow conditions.

If placed in a pool or behind a weir, the OBS meters can also subject to burial by bedload. Even if not buried, accumulation of gravel to within 10 cm or so below the sensor can result in erroneous high readings as the light beam "sees" the gravel bed. In a shallow stream, placing the OBS meter is a trade-off between interference by the bed if placed too deep, or interference by sunlight if placed too shallow.

In addition to the fairly obvious problems described above, we have had a considerable amount of lost data for unknown reasons, most often during high-turbidity periods. A possible reason for this might be sporadic out-of-range signals caused by debris in the water. OBS meters return quite a high signal compared to most non-optical instruments used in hydrology and meteorology. If these signals are much greater than the maximum signal which can be accepted by the CR10, they can cause loss of the entire 15-minute data period, and also shut down the signals of other instruments connected to the CR10. For most days during the high flow period, the maximum instantaneous turbidity recorded from the OBS meter is several times greater than the maximum 15-minute value, and is often equal to the maximum signal the data logger is capable of receiving (2500 mV, corresponding to about 500 NTU on our instruments). We are trying to avoid this problem by having our OBS meters modified to work on a 5 V power supply instead of 12 V, which should reduce the maximum signal returned by the OBS meter if its beam is totally obstructed by a reflecting object. It may also be possible to reduce the data loss problems by using voltage dividers, or by adding signal-conditioning routines to the data logger programs. However, these solutions carry a cost in lower precision of the measurements, or in increased complexity of the installation or the data logger program, which may introduce other opportunities for error, as well as increasing the demands on the skill and time of technicians installing and maintaining the sites.

A final problem we have experienced is battery failure, especially in the autumn when temperatures drop below freezing. This can be solved most simply by more frequent inspection, or otherwise by using solar panels or by programming the data loggers to operate the OBS meters intermittently, or shut them down if battery voltage drops to a certain level.

Our instrument sites are located in a populated, easily accessible area, only 30 minutes by vehicle from our headquarters. Also, the creeks are not subject to a high risk of extreme flooding, channel shifting, or debris movement, compared to creeks in many other regions of the province. We are able to visit the sites frequently and on short notice, and we have not experienced any events which caused major damage to the sites. Despite these advantages, loss or corruption of data due to the causes described above has been a significant constraint to using OBS meters as our main device for collecting sediment data.

Conclusions

The main value of turbidity measurement using OBS meters in this study has been to extend the point observations of individual sediment samples to a continuous record. Since suspended sediment concentration is extremely variable over time, a single water sample per day is unlikely to give a representative value. Continuous turbidity records enable us to more accurately estimate suspended sediment yield, and to identify short-duration sediment events which are likely to be missed by sampling.

However, the use of OBS meters has some significant limitations under field conditions. We have experienced a high incidence of missing data, due to both unavoidable hydrologic causes and partly avoidable instrument problems. The OBS meters require frequent inspection and maintenance to prevent fouling by debris and algae growth. Peak values of apparent turbidity are usually caused by events other than high sediment concentration.

Drift of the zero of the instrument is a problem, which can be corrected if frequent water samples are taken. For this reason, and for others including limits of precision of lab turbidity and suspended sediment measurements, OBS meters are not very useful for measurement of low turbidity water (< 1 NTU or < 5 mg/l).

Analysis of turbidity data collected by OBS meters is time-consuming; a lot of "cleaning up" is necessary to correct data, deal with gaps of missing data, and reject spurious data.

A concurrent program of manual sediment sampling is essential. Sediment budgets studies or sediment monitoring programs cannot be based on OBS turbidity measurements alone.

Acknowledgments:

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References:

Church, M., Kellerhals, R., and Day, T.J. 1989. Regional clastic sediment yield in British Columbia. Canadian Journal of Earth Sciences, 26: 31-45.

TABLE 1. SUSPENDED SEDIMENT YIELDS, REDFISH AND LAIRD CREEKS, SPRING FRESHET PERIOD OF 1993 AND 1994

	Yield (Tonnes)	(Tonnes/km^2)
Redfish Creek (26.2 km^2)		
1993	220	8.4
1994	58	2.2
Laird Creek (15.0 km^2)		
1993	61	4.1
1994	20	1.3

Estimated sediment sources from road erosion (Redfish Creek, measured sites only)
Second column is based on average grain size distribution of source areas, of 25% suspended size (< 0.5 mm) and 75% bedload size.

	Total eroded sediment	Suspended sediment
1993	133 Tonnes	33 Tonnes
1994	13 Tonnes	3 Tonnes

TABLE 2. REDFISH CREEK 1993: TOTAL SUSPENDED SEDIMENT DURING SPRING FRESHET, CALCULATED BY THREE DIFFERENT METHODS

Calculation method	Yield in Tonnes
OBS meter - continuous turbidity record (15 minute averages)	220
OBS meter - daily average turbidity	213
daily sampling of suspended sediment	246

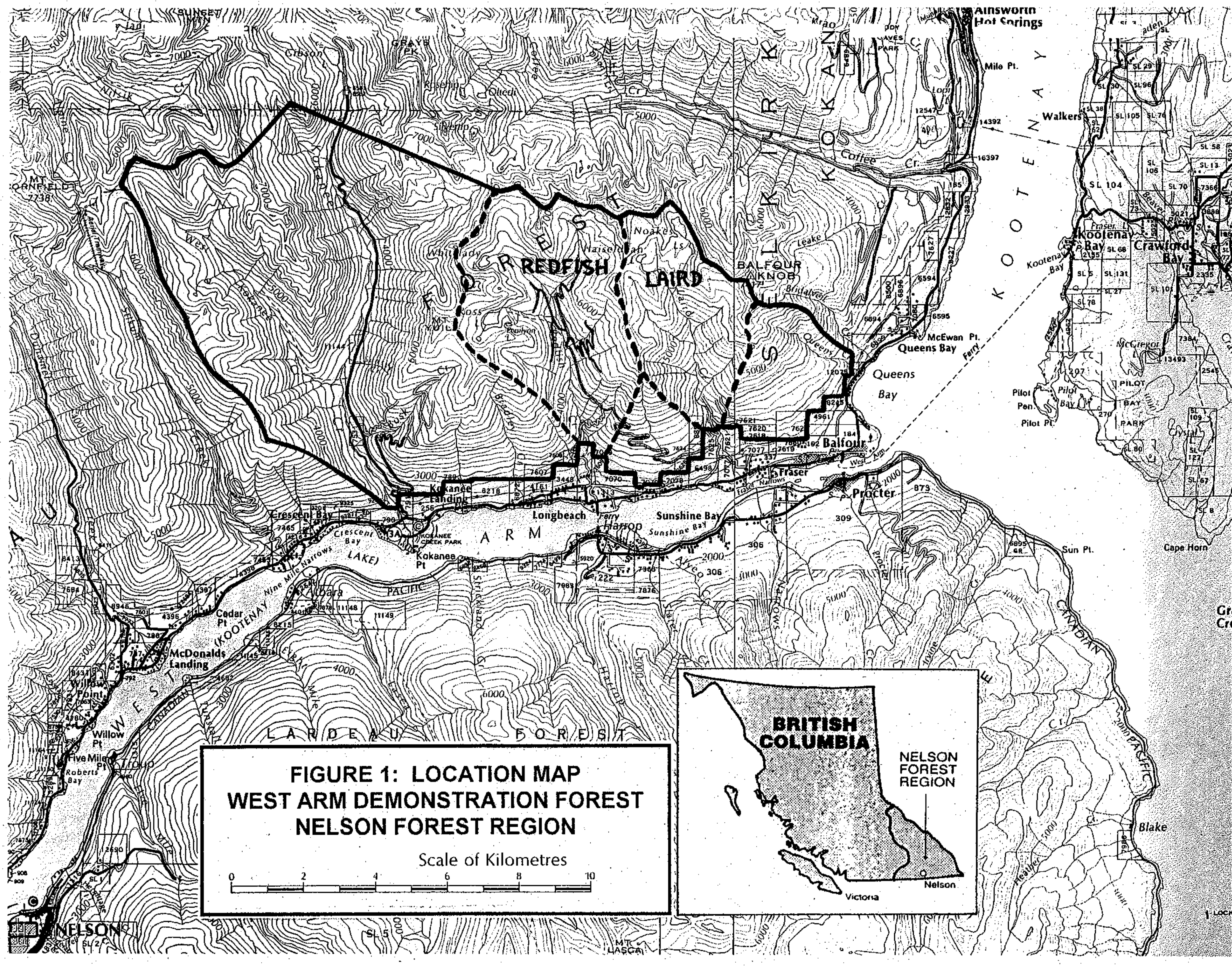

FIGURE 1: LOCATION MAP
WEST ARM DEMONSTRATION FOREST
NELSON FOREST REGION

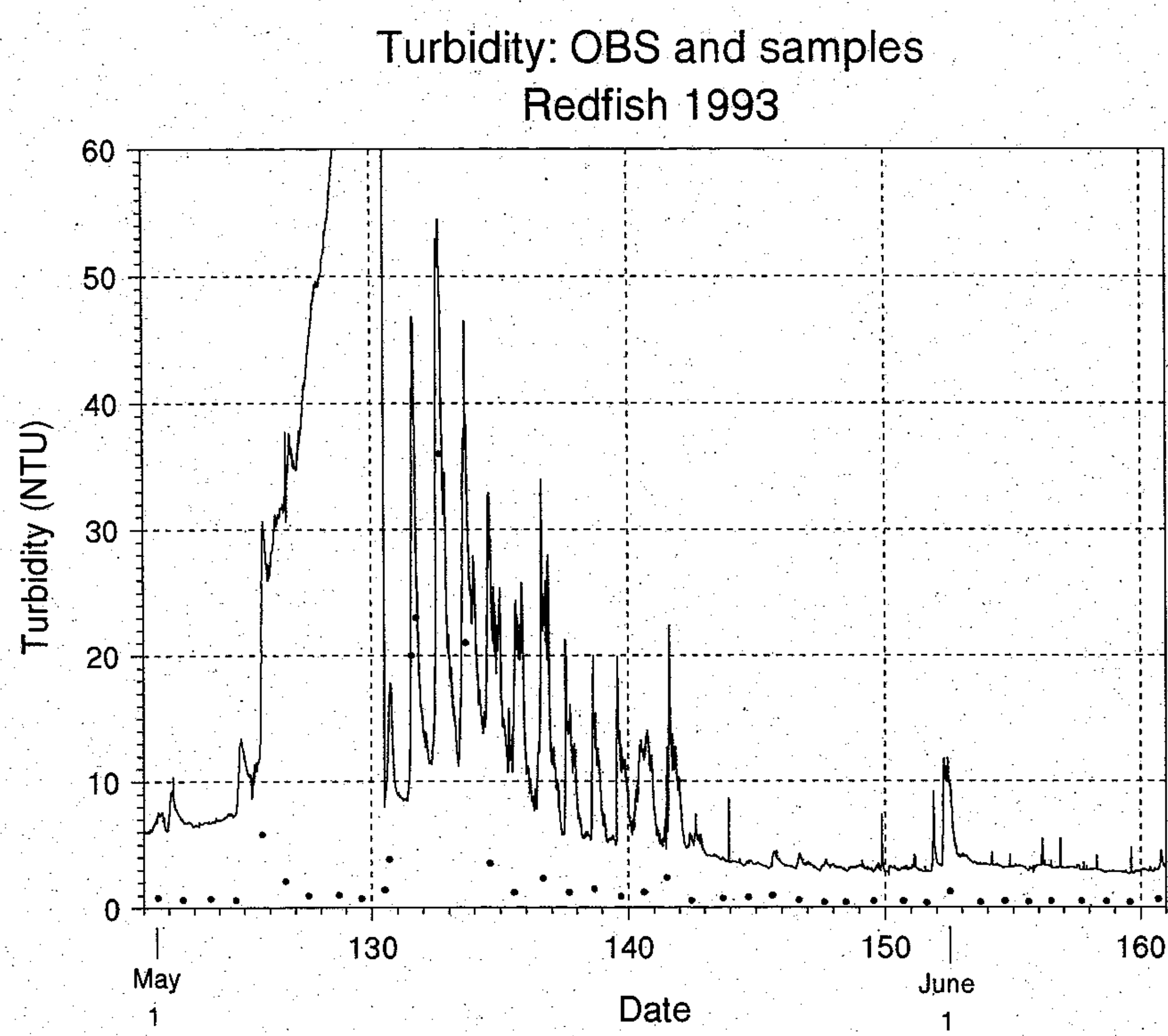

FIGURE 2. Uncorrected turbidity from OBS meter, and turbidity of daily water samples, for Redfish Creek during spring freshet, 1993. Dates are in Julian days. High turbidity values from day 126 to 130 are due to fouling of the OBS meter.

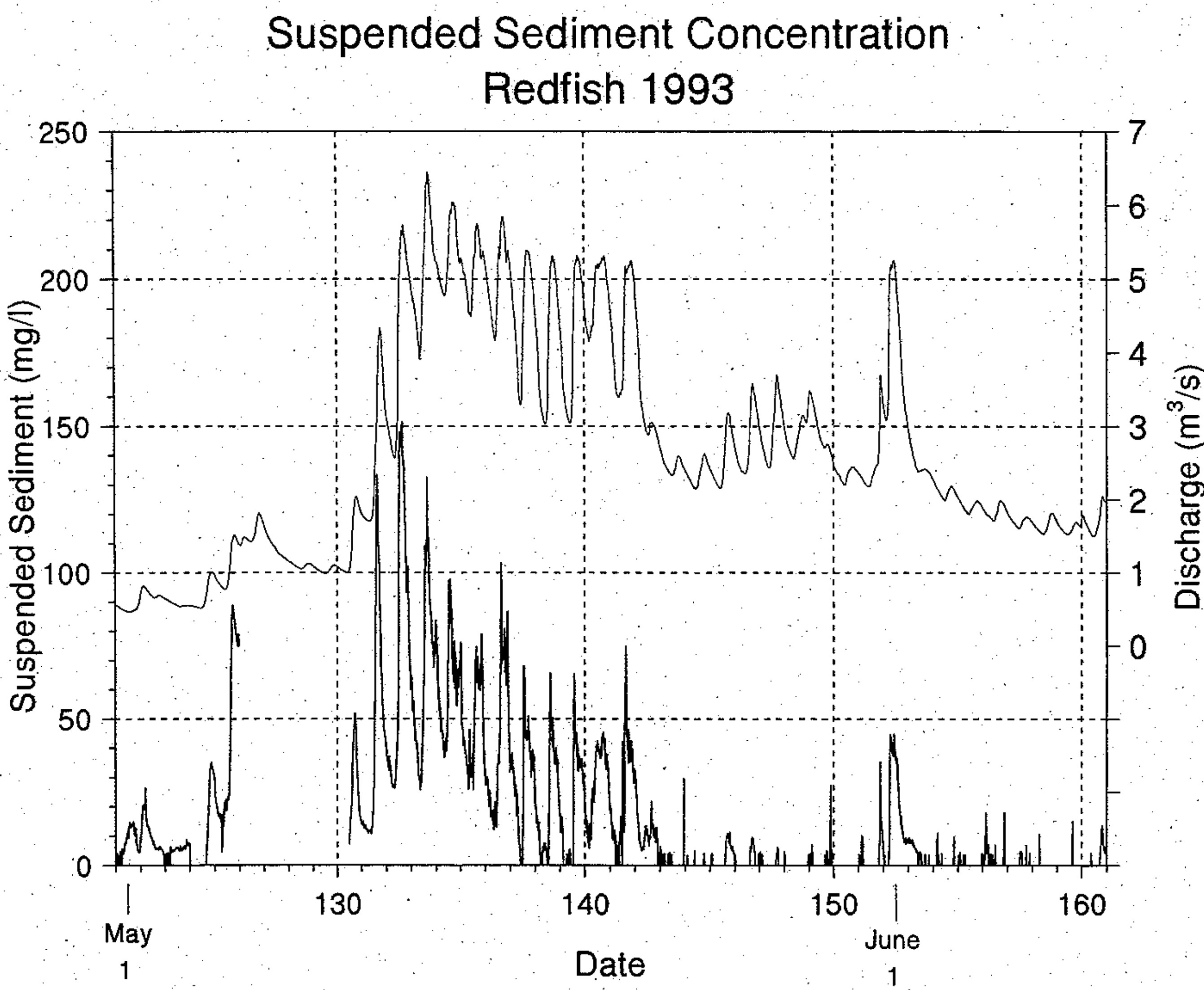

FIGURE 3. Discharge and calculated suspended sediment concentration. Sediment concentration is calculated from turbidity using the regression relation in Figure 5.

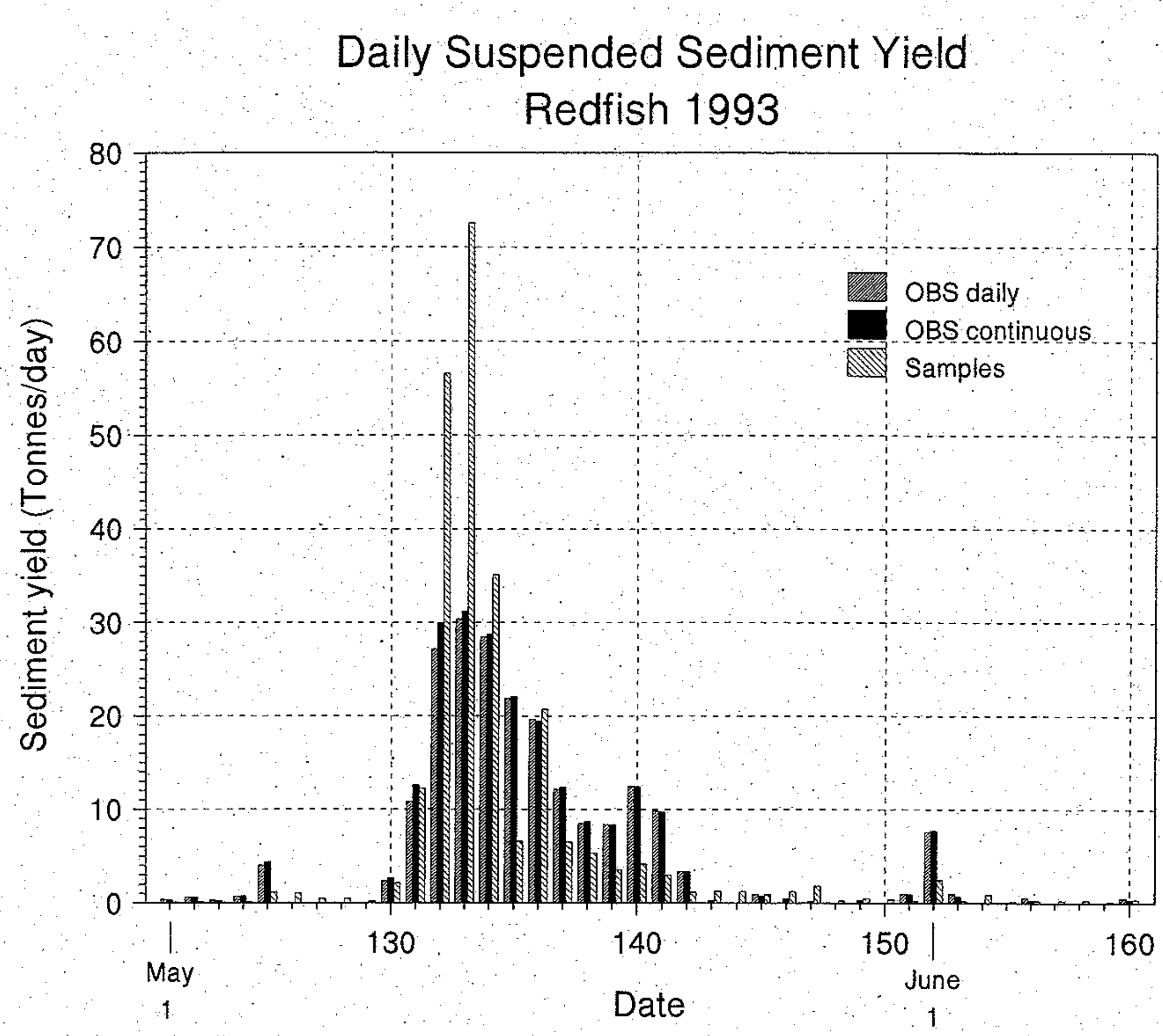

FIGURE 4. Calculated daily suspended sediment yield, for same period as Figures 2 and 3. "OBS daily" is calculated as the product of daily average sediment concentration and discharge. "OBS continuous" is calculated from 15-minute averages. "Samples" is calculated from the daily sediment sample.

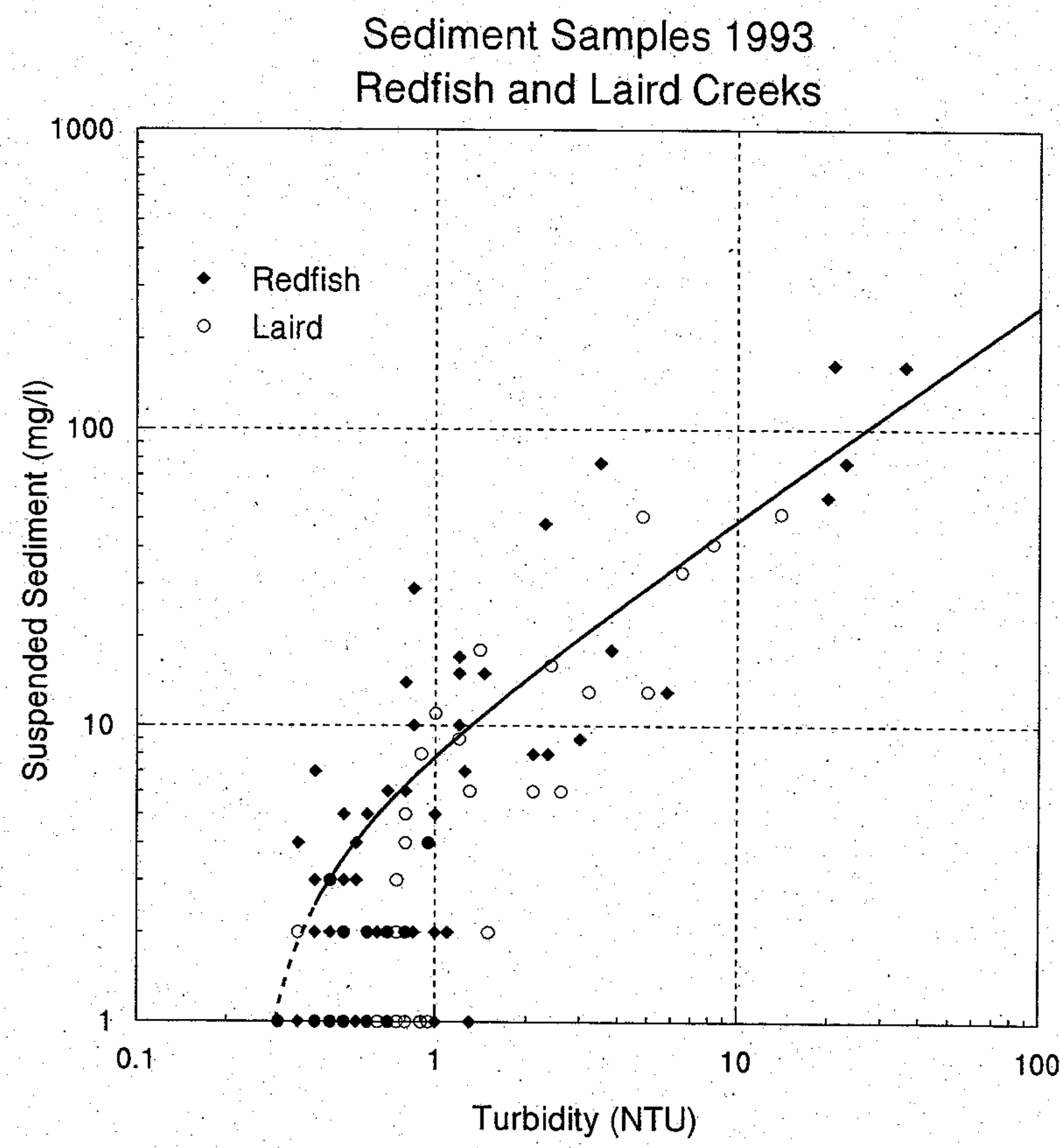

FIGURE 5. Regression of suspended sediment concentration on turbidity, for 1993 sediment samples. The regression includes Redfish samples with concentration > 2 mg/l, only. The independent variable is (turbidity - 0.25 NTU).

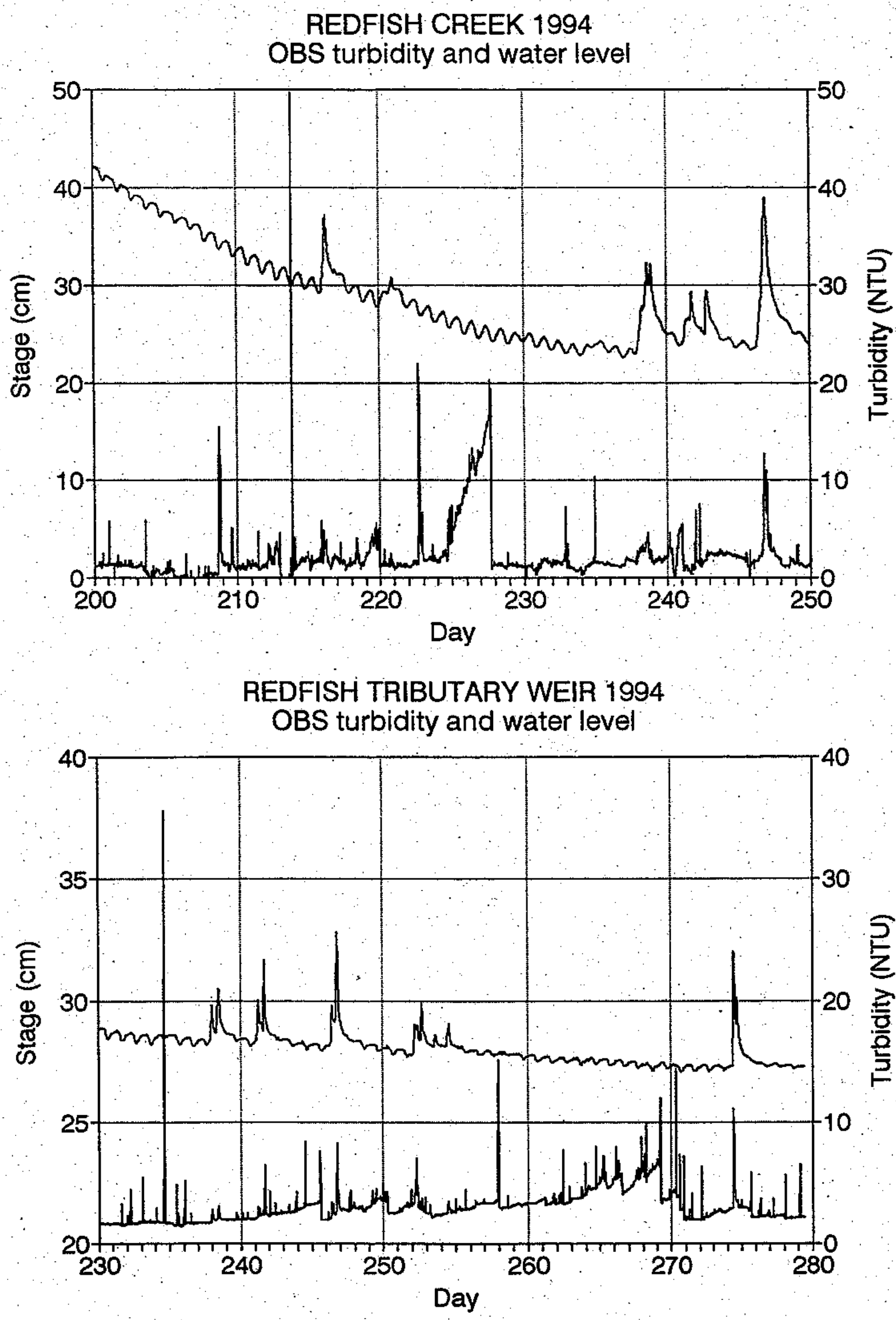

FIGURE 6. Examples of raw data: stage (top line in each graph) and turbidity (bottom line), for two stations in late summer. The graphs illustrate drift of the OBS meter zero, due to fouling of the sensor by algae and other unknown effects. At most times other than during rainstorms, the turbidity as measured in water samples was near zero (less than 0.5 NTU).