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# An inexpensive turbidimeter for monitoring suspended sediment

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**Abstract**

Temporal and spatial variability of suspended sediment in proglacial streams means that discrete monitoring is unlikely to characterize suspended sediment patterns accurately. Continuously recording turbidimeters provide a solution to the temporal problem of sampling. However, the problem of spatially limited sampling is constrained largely by the cost of establishing networks of commercially available turbidimeters. In this paper we present the design and testing of an inexpensive, custom-built, datalogger-compatible and rugged infrared nephelometric turbidimeter (the "HOBS"). Laboratory testing showed that the HOBS was most sensitive to coarse clay and fine silt fractions, the dominant particle sizes transported in proglacial streams. Further testing showed that the HOBS had a non-linear but regular response to bulk sediment concentrations from 0 to ~3500 mg $L^{-1}$, with explained variances of 99.2% to 99.8%. In the field, the HOBS showed a linear response up to 2000 mg $L^{-1}$ and a non-linear response up to 10,000 mg $L^{-1}$ with explained variances between 75% and 83%. This variability emphasizes the necessity of individual, site specific field calibrations. The HOBS's sensitivity to a wide range of suspended sediment concentrations is particularly suited for use in proglacial streams where large fluctuations in concentration are likely. The generic design, low cost, and good performance of the HOBS suggests potential for application in other environments where distributed monitoring of suspended sediment is of interest.


*Keywords:* Turbidimeter; Proglacial streams; Suspended sediment; Small River Glacier

## 1. Introduction

Proglacial streams transport significant amounts of sediment maintained in suspension by turbulence. This suspended sediment has been used to indicate water quality and as an index of sediment mobilization within glacierized landscapes (e.g., Hammer and Smith, 1983; Hallet et al., 1996; Willis et al., 1996). However, continuous monitoring of suspended sediment concentration in proglacial streams has shown high variability over time (Gurnell and Warburton, 1990). The utility of suspended sediment as an indicator relies, therefore, not only on accurate determination of concentration, but also on sufficiently frequent sampling (Clifford et al., 1995a,b).

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Although automatic water samplers and USDH-48 depth-integrated samplers can provide unbiased point estimates of suspended sediment concentration, processing time often limits sampling frequency to discrete, hourly observations (Gurnell et al., 1992a; Wren et al., 2000). Discharge/suspended sediment concentration rating curves are commonly used to overcome this problem as discharge can be monitored relatively easily. However, discharge and suspended sediment concentration are often only weakly related because of spatial variations in channel sediment supply and availability, inputs from tributaries and delivery unrelated to discharge (e.g., bank collapse) (Hammer and Smith, 1983; Richards, 1984; Fenn et al., 1985; Gippel, 1989; Walling et al., 1992). Temporally discrete and spatially limited sampling is unlikely, therefore, to provide accurate characterization of proglacial suspended sediment transfer patterns (Orwin and Smart, 2004a).

A solution to the limitations of discrete sampling is the use of continuously recording turbidimeters in the field (Gippel, 1989, 1995; Gurnell and Warburton, 1990). However, continuous records of turbidity do not resolve the problem of spatially limited sampling. This is partly due to the high cost of establishing networks of commercially available turbidimeters. An alternative to purchasing commercial turbidimeters is to design and construct an inexpensive, custom-built instrument. This paper details the design and performance of such a turbidimeter (the HOBS—"Harry's Optical Backscatter Sensor") developed for spatially distributed monitoring of suspended sediment in proglacial streams. The main design objective is to build an instrument with low power consumption, datalogger compatibility and sensitivity to the dominant particle size carried in proglacial streams. The HOBS suitability for monitoring proglacial suspended sediment is evaluated by comparing its response to changes in particle size with a commercial turbidimeter in the laboratory. The effectiveness of the HOBS in determining suspended sediment concentration is determined using bulk field sediment in the laboratory, and its field performance assessed from a network installed for one ablation season in two proglacial streams at Small River Glacier in the Canadian Rockies.

## 2. Design of the HOBS

### 2.1. Electronics

The sensor array for the HOBS is based around a high-power GaAlAs infrared light emitting diode (LED) manufactured by Opto Diode (Part # OD-880E). This LED is designed for maximum emittence at 880 nm with a spectral bandwidth of 80 nm at 50% peak output. The detector is a matching, high sensitivity GaAlAs photodiode (Part # ODD-95W) with peak sensitivity also at 880 nm and a spectral bandwidth of 60 nm at 50% peak output. Both the emitter and photodiode provide a narrow and closely matched spectrum approximating to maximum sensitivity to coarse clay and fine silt, usually the dominant particle size transported in proglacial streams (Gurnell, 1987).

Conversion of the photodiode current and amplification of the voltage is achieved by using two low noise, stable, high speed, precision JFET Input operational amplifiers manufactured by Linear Technologies (LT1055), designed specifically to work with high-sensitivity photodiodes. The gain can be adjusted from 10 to 110 times, if necessary, through a trim pot mounted on the circuit board. Power requirements for the HOBS are $\pm$12V (converted using an Intersil ICL7662 PCA CMOS voltage converter) for the operational amplifiers, and 5 V for the infrared emitter. Power consumption is low, requiring currents in the order of ~5.6 mA for the detector and output and ~126 mA for the emitter. The sensor array is mounted on the HOBS circuit board in a 180$^\circ$ backscatter geometry for ease of construction. A full circuit diagram is shown in Fig. 1.

### 2.2. Construction of the casing and casting of the HOBS

An important design criterion for the HOBS was that the casing be rugged enough to withstand use in proglacial streams for extended periods of time. Black 42 mm (34 mm ID) ABS plastic tubing was used for the external casing. The circuit board was mounted with epoxy onto a 30 mm (23 mm ID) PVC pipe half, which was then set into the ABS pipe using epoxy "ball" spacers (Fig. 2). A small piece of black ABS sheet was placed between the infrared emitter and the

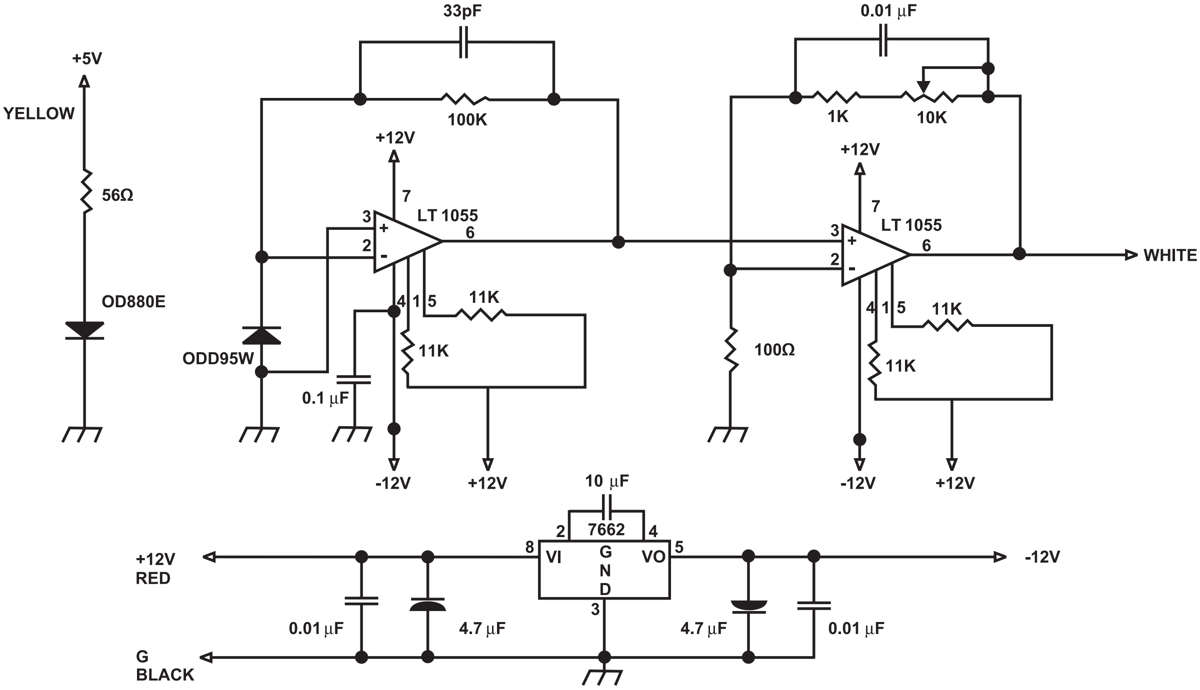


Fig. 1. Circuit diagram for the HOBS turbidimeter.

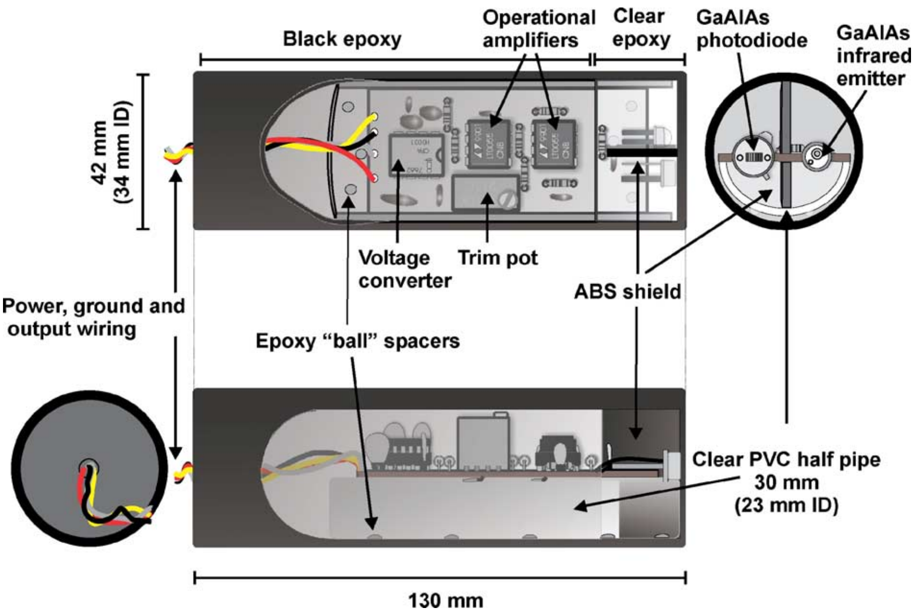


Fig. 2. Plan and side "cutaway" schematic diagram of the finished HOBS. Finished length is after approximately 10 mm of the clear resin covering the sensor end had been machined to a flat surface and polished (to within 2 to 3 mm of the infrared emitter and photodiode).

photodiode as a shield to ensure there was no internal reflectance. The sensor array and ABS shield was offset from the end of the half pipe by ~10 mm to allow space for the encapsulation and finishing of the sensor face.

Crystal Clear 200™, a rigid urethane casting resin manufactured by SmoothOn Products™ was used to encapsulate the circuit board. This resin is designed specifically for applications that require optical clarity and has low viscosity, a 20 min pot life, and negligible shrinkage (0.033 mm $mm^{-1}$). The full cure time for Crystal Clear 200™ is ~16 h with ultimate physical properties being reached after 5 days (manufacturer data). Cured castings are also UV stable, completely waterproof and can be polished to an optically clear finish.

The HOBS was cast in two stages to ensure the integrity of the circuit board and sensitivity to the turbidity signal only. Before the first cast, the mounted circuit board inside the ABS pipe (sealed with plastic wrap at the sensor end) and a vial of ~60 ml of Crystal Clear 200™ (enough to cover the first 25 mm of the sensor array) were vacuum pumped a minimum of three times to remove air bubbles. Following vacuum pumping, the clear resin was poured slowly down the sidewalls of the ABS pipe, which was then stood vertically to allow the resin to level over the sensor array. While the clear resin was curing, a further 120 ml of resin was mixed with black dye and also degassed using vacuum pumping. This second cast of black resin was then slowly poured down the sidewalls of the ABS pipe until the circuit board was completely covered to ensure complete protection from moisture and shock, leaving only the four connecting wires exposed. The completed casting was then set in a rack and allowed to cure for 5 days at room temperature. The double cast and the black ABS shield ensured that no extraneous infrared light could be refracted through the casting to interfere with the turbidity signal received by the photodiode.

After curing, the clear resin covering the sensor array end of the ABS pipe was machined down to within ~2 to 3 mm of the infrared emitter and photodiode to achieve a flat surface. This surface was then polished with glass-mounted, wet sandpaper progressively from 200 to 2000 grit to produce a clear, flat finish to the sensor array face (Fig. 2).

### 2.3. Datalogger compatibility

The HOBS circuitry was designed to be compatible with standard dataloggers. As the instrument requires a 12V DC power source for the detector and amplifiers, a 5 V source for the LED and generates a mV output signal, we used Campbell Scientific 21X and CR-10 dataloggers. These dataloggers are programmable and have the option of switching the 5 V power source that conserves power. A switchable power source also allows the datalogger to be programmed to delay switching on the LED. This enables a null background reading to be determined from the detector. By subtracting the background reading from the signal with the LED switched on, a "true" turbidity measurement can be obtained. The datalogger can be further programmed to obtain compound averages of a number of background and turbidity readings. This option allows compilation of longer-term averages as a form of data compression and noise rejection.

### 2.4. Temperature effects

Fluctuations in water temperature can potentially affect electronic components and cause output signal errors in turbidimeters (Lawler and Brown, 1992). The electronics of the HOBS were therefore tested for these effects by immersing a completed instrument in an ABS tube filled with laboratory grade optically clear water and cooling to 0.1 °C. The tube and instrument were then placed in a water jacket at room temperature. Water in the tube was gradually heated to 38 °C using a combined hotplate/magnetic stirrer and the HOBS output recorded every second. This was repeated with two other duplicate instruments. Results showed no significant temperature effect in the three output signals.

## 3. Laboratory testing

The objective of the laboratory testing was to validate the HOBS design for monitoring proglacial suspended sediment before use in the field. This was done in two stages. The first stage examined the influence of particle size distribution, and the second, calibration of the HOBS with bulk suspended sediment. Response to particle size was compared with that of an OBS-3 infrared nephelometric turbidimeter manufactured by D&A Instruments. The OBS-3 functioned as a control for the expected response as this instrument also operates in the infrared spectrum and has similar backscatter geometry (between 140° and 160°) (Downing, 1991).

### 3.1. Laboratory sediment characteristics

Sediment was obtained from deposits on the surface of channel boulders exposed under low flow at Small River Glacier, British Columbia, Canada. X-ray diffraction on a sediment sample showed that the mineralogy is dominated by quartz (~40%) and calcite (~35%) with lesser percentages of mica (~10%) and dolomite (~5%). The remaining 10% is predominantly clay minerals. Sediment for particle size response was fractionated using a combination of wet and dry sieving and pipetting from settling columns. Sediment sizes were measured with a Malvern Mastersizer 2000 with samples dispersed using sodium metaphosphate ($(NaPO_3)_{13}NaO$) and four sediment size classes assigned based on Wentworth (1922). The $d_{50}$ for fine/very fine sand was 120 μm, silt, 6.6 μm, and coarse clay and fine clay ~2.19 and 0.16 μm, respectively. The coarse and fine clay particle sizes were run together and the $d_{50}$ values should be taken as estimates only. Additional sediment was wet sieved and the fraction less than 63 μm retained as representative of bulk suspended sediment ($d_{10}$ to $d_{90}$: 2.22 to 16.9 μm, $d_{50}$: 5.73 μm) (Fig. 3).

### 3.2. Methods

#### 3.2.1. Response to particle size

To measure the response of the OBS-3 and HOBS turbidimeters to changes in particle size distribution, a 300×100 mm black ABS tube was filled with 2000 ml of laboratory grade reagent water passed through a 0.02 μm filter to ensure optically pure water (Eaton et al., 1995). The respective sensor heads were submerged under 50 mm of water, with at least 250 mm of water between the base of the tube and the sensor array to ensure there was no reflectance or absorption of the infrared signal by the base of the tube (Downing, 1991).

A suspension of known concentration was formed by dispersing a weighed (to a precision of 0.0001*g*) amount of dry sediment into the water. Suspension was maintained using a magnetic stirrer. Sediment was progressively added to increase concentration until each turbidimeter's output plateaued. Thirty measurements at 4 s intervals were recorded for each concentration after the suspension had mixed for 1 min. Complete disaggregation of the sample was assumed. On average, 25 different concentrations were measured, ranging from 0 to 4500 mg $L^{-1}$ for

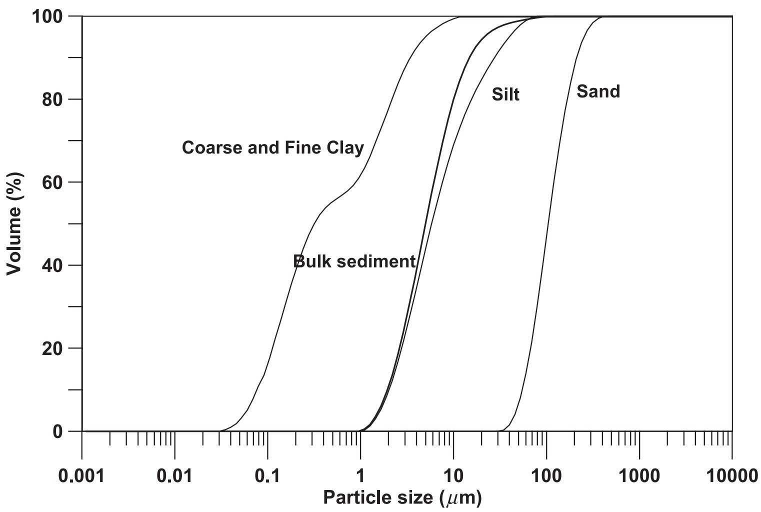


Fig. 3. Particle size distributions using a Malvern Mastersizer 2000 laser particle size analyzer for the four particle size classes and the bulk sediment.

the HOBS and 0 to 2500 mg $L^{-1}$ for the OBS-3, whereby the OBS-3 standard factory-set range was exceeded. An identical procedure was run for each size fraction after thorough cleaning of the tube and sensor face with detergent and deionized water between runs.

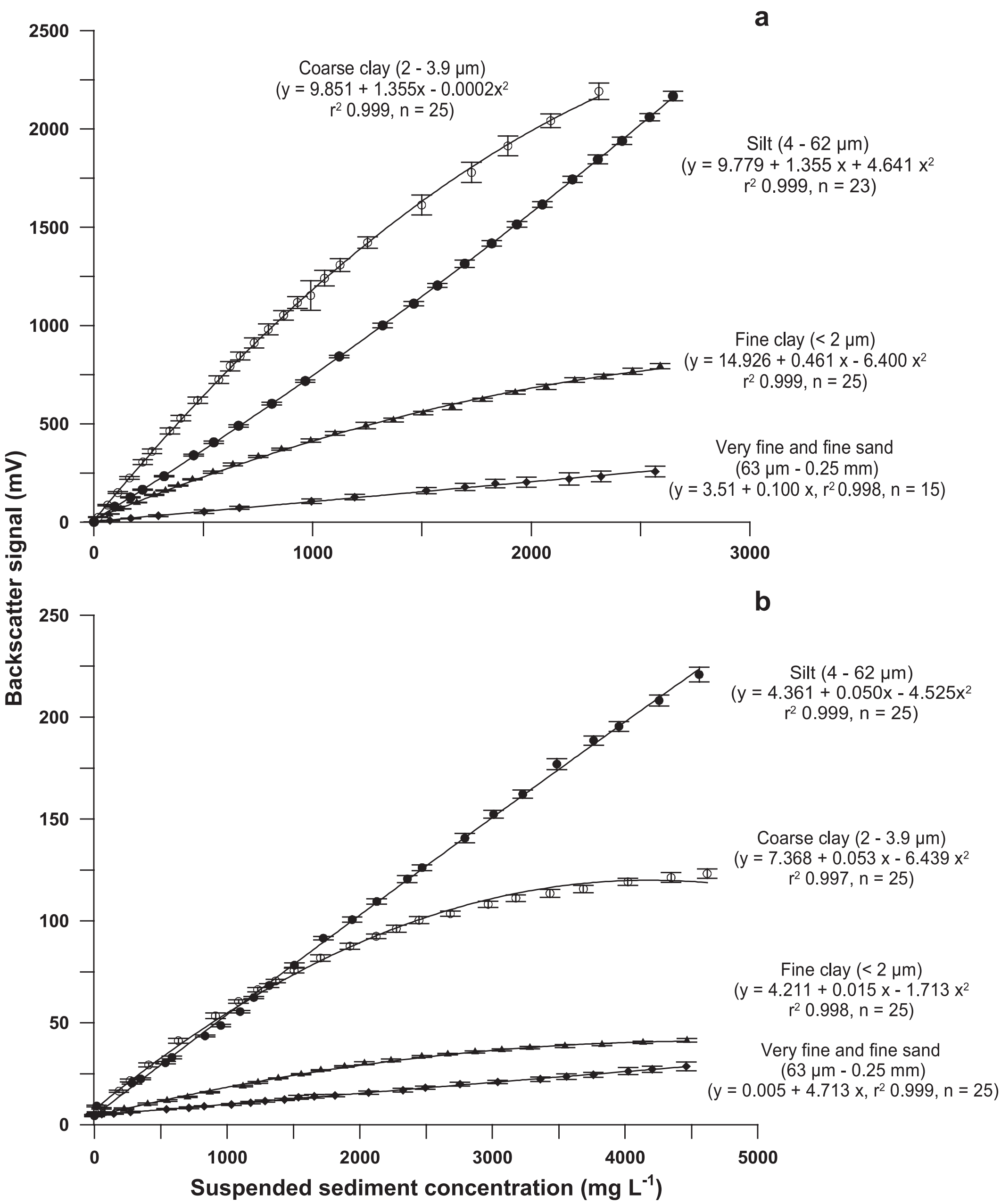


Fig. 4. (a) The response of the D&A Instruments OBS-3 turbidimeter to particle size. Each point represents the average of 30 measurements with ±2 standard deviations indicated. Best-fit equations are shown. The maximum concentration tested was ~2500 mg $L^{-1}$, where the factory set range of the OBS-3 was exceeded. (b) The response of the HOBS to particle size. Each point represents the average of 30 measurements with ±2 standard deviations indicated. Best-fit equations are shown.

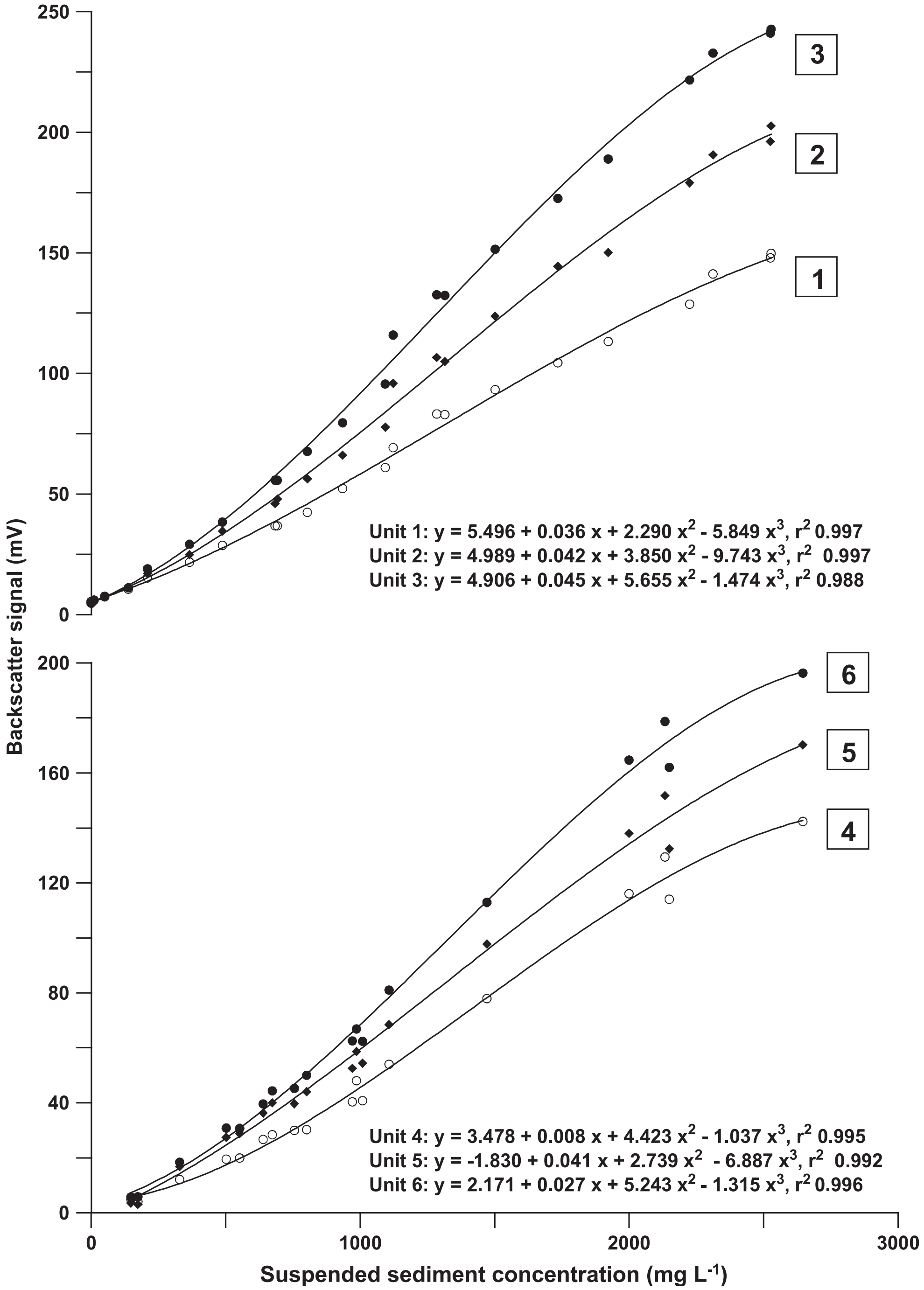


Fig. 5. HOBS laboratory calibration with bulk sediment from Small River Glacier. The graphs presented are from six duplicate instruments. Best fit, 3rd order polynomial equations are shown.

#### 3.2.2. Bulk sediment

Calibration of the HOBS using bulk suspended sediment was based on Downing (1991). A black (250 mm ID, 20 L volume) plastic bucket was filled with optically clear water. Each sensor was suspended from a wire across the middle of the bucket with the sensor face ~50 mm below the water surface with at least 250 mm of water between the base of the bucket and the sensor array.

Concentration was adjusted by progressively adding arbitrary masses of bulk sediment already in suspension to the bucket. A stirrer attached to a handheld drill kept the sediment in the bucket in suspension. Sampling interval was set at 4 s. After each addition of sediment, a reading was taken once the output signal stabilized (usually 5 to 10 s) and a concurrent 10 ml sample was pipetted, using a wide-bore pipette level with the sensor face, and placed in a pre-weighed, dry aluminum dish. Sediment was added in approximately 19 increments to generate calibrations from 0 to a maximum of ~3500 mg $L^{-1}$. On completion of each run, the samples plus dishes were weighed (to a precision of 0.0001*g*) and oven dried for 24 h at 105 °C as per APHA Method 2540B (Eaton et al., 1995). Dried samples were re-weighed and the suspended sediment concentration determined to a precision of ~±6.0 mg $L^{-1}$ (Eaton et al., 1995). Six runs were done using six different HOBS.

### 3.3. Results

#### 3.3.1. Particle size

The OBS-3 was most sensitive to coarse clay, and then to silt, followed by fine clay and fine/very fine sand (Fig. 4a). Only the silt and sand calibrations appeared to correspond to the expected linear response to changes in suspended sediment concentration, with an explained variance of 99.8% from a linear regression fitted to the silt data. However, a residual plot for the silt run showed that the response was non-linear. Fitting the second-order polynomial recommended by the technical manual of the OBS-3 for precise fits (Downing, 1991) gave an explained variance of 99.9%.

Over the equivalent range of concentrations, the HOBS showed greatest sensitivity to silt, with a similar sensitivity to coarse clay up to ~1200 mg $L^{-1}$ (Fig. 4b). The slopes of the HOBS response to coarse clay and silt were not statistically different (at $\alpha$=0.05) up to this point, after which the sensitivity to coarse clay decreased. The HOBS showed a relative lack of sensitivity to fine/very fine sand, matching the OBS-3, but was less sensitive to fine clay. A linear fit to the HOBS silt calibration had an explained variance of 99.9% but correlated residuals indicated a non-linear response. A second-order polynomial gave a better fit. A replicate for the silt calibration gave similar results. The HOBS sensitivity to silt and coarse clay validated the design for monitoring proglacial suspended sediment.

#### 3.3.2. Bulk sediment

The consistency of the HOBS calibration between instruments is shown by the similarly shaped third-order polynomials for six instruments (Fig. 5). Differences in the slopes were most likely due to slight variations in gain settings on individual instruments. Scatter around individual curves increased with suspended sediment concentration, but overall the HOBS predicted concentrations from 0 to ~3000 mg $L^{-1}$ with explained variances between 99.2% and 99.8%. The maximum concentration expected at the Small River Glacier site was ~3500 mg $L^{-1}$ (Lockrey, 1996) and performance up to this maximum was an important component of the HOBS design.

## 4. Field testing

### 4.1. Field site

The HOBS was field-tested in the Small River Glacier catchment in the summer of 2000. The catchment area is 6.86 $km^2$, with the glacier occupying approximately 50% (see Orwin and Smart, 2004a,b for more detail on the field area). Four HOBS were installed in series on a proglacial stream draining the main glacier and a further four installed in a second stream draining a stagnant lobe and a small, isolated cirque glacier. The main stream was characterized by large diurnal fluctuations in suspended sediment concentration (typical range 0 to 3500 mg $L^{-1}$) with concentrations in the second stream typically fluctuating between 0 and 300 mg $L^{-1}$. This wide range of concentrations and a field season of 9 weeks allowed practical assessment of the HOBS field performance.

### 4.2. Installation of the HOBS

The potential for solar infrared interference during low stage presented some problems for the installation of the HOBS network. Although infrared wavelengths are strongly attenuated in water (~63% reduction per 50 mm in clear water; Downing, 1991), maintaining sufficient water depth to achieve this attenuation is difficult in small, variable-stage proglacial streams. Therefore a casing was designed to screen the HOBS from solar infrared interference and to also protect it from the impact of large particles moving as bedload during storm events. However, the insertion of any turbidimeter into a stream disrupts natural water flow and may therefore result in readings that are not necessarily representative of the actual suspended sediment concentration. Although we recognize the flow disruption by the casing used in this study as a potential limitation, its use was largely unavoidable in order to collect continuous data and to protect the instrument.

The casing was constructed from an 1830×152 mm section of ABS pipe. A gooseneck fitting was drilled and tapped onto the pipe at the downstream end (Fig. 6). A 6 mm galvanized steel mesh placed over the upstream end prevented large sediment particles from entering, damaging the turbidimeter and choking the pipe. The design ensured complete immersion and a continuous flow of water past the turbidimeter even under low flow. The HOBS was welded with ABS cement to an ABS-threaded female

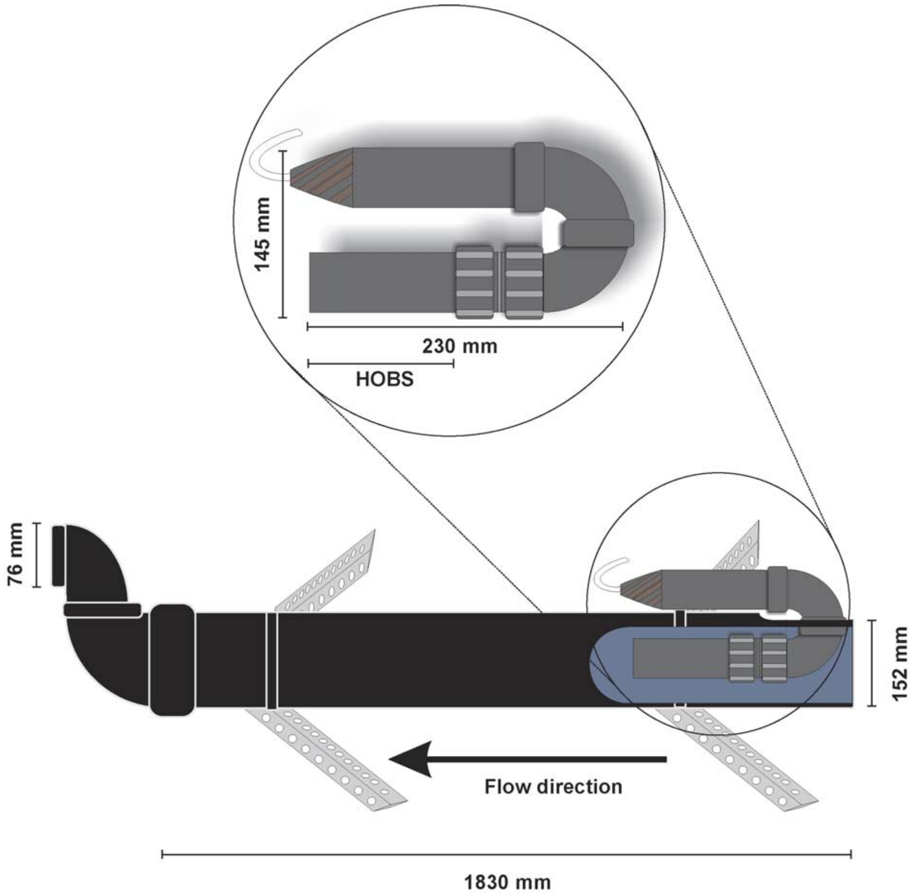


Fig. 6. Schematic and “cutaway” of the casing used to protect the HOBS from solar infrared saturation under low stage and the impact of large particles moving as bedload. Also shown is the U-section of ABS pipe used to attach and insert the HOBS into the casing. Once inserted, the U-section was clamped to the casing using a hose clamp and duct tape. Note that the 6 mm steel mesh netting on the upstream intake is not shown.

connector and screwed to a sealed, U-shaped section of ABS piping for easy insertion and removal from the casing (Fig. 6).

Dexion™ fins were hose-clamped to the casing and weighted by rocks imbricated against the stream flow to fix the device to the channel bed. The fins

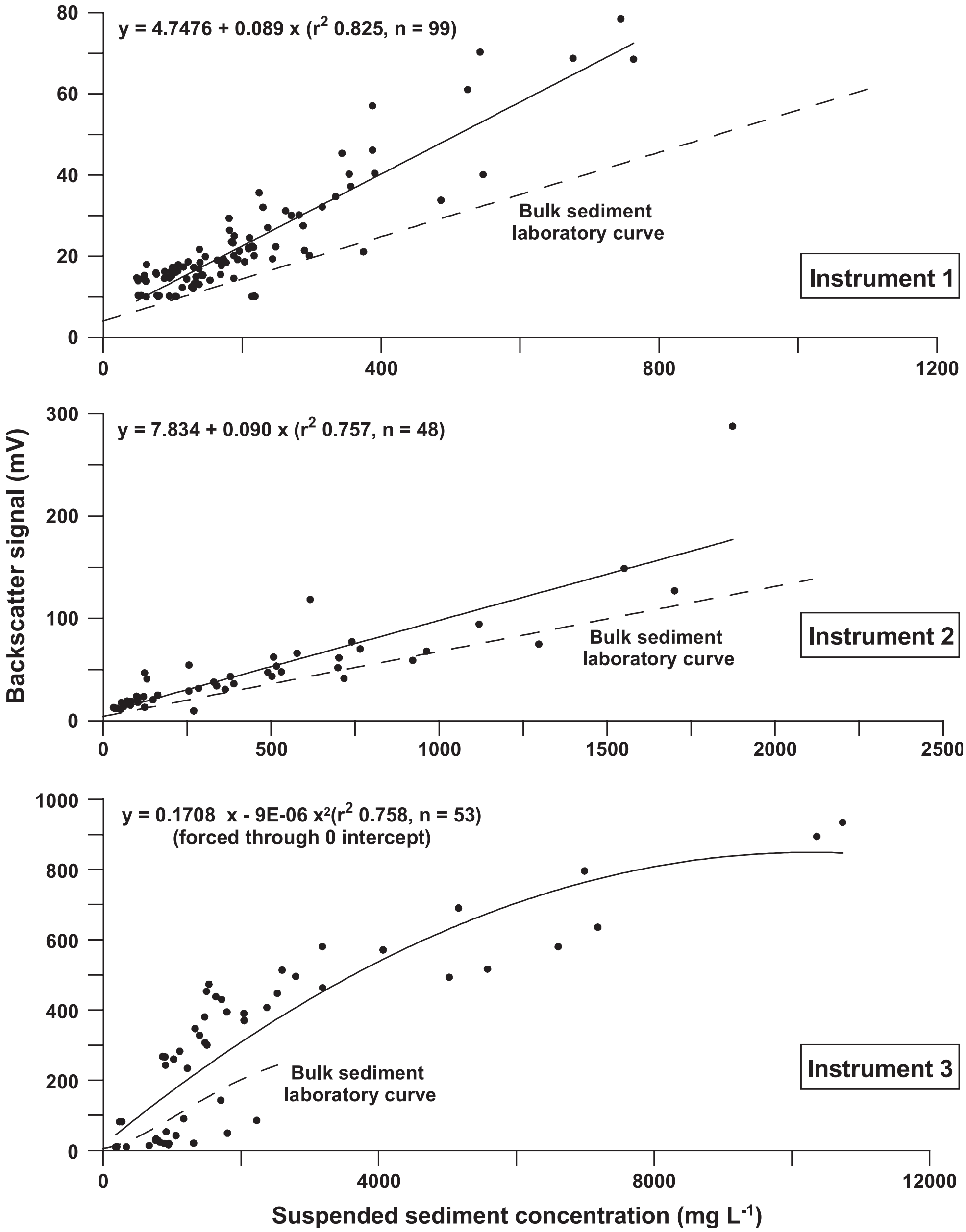


Fig. 7. Representative field calibrations from Small River Glacier for three HOBS over different ranges of suspended sediment concentration. Linear regression equations are shown for the first two instruments and a 2nd order polynomial equation for the third. Instruments 1 and 2 were installed on a stream draining a stagnant lobe and a small cirque glacier, the third on a stream draining the main glacier. The bulk sediment laboratory curves for the instruments are for the corresponding individual HOBS (see Fig. 5).

enabled the upstream end of the device to be elevated above the streambed to prevent burial of the intake and to ensure that only suspended sediment was being measured (under non-storm flow).

### 4.3. Methods

Each of the eight turbidimeters was connected to either a Campbell Scientific CR-10 or 21X datalogger and programmed to make five background and turbidity readings every 10 s with net turbidity averaged and stored every 5 min. Power supply for the dataloggers was provided by NiCad batteries charged by solar panels.

Stream water from automatic samplers was used to establish the relationship between turbidity and suspended sediment concentration for each turbidimeter, in situ. At each site, water samples were taken every 2 h, using an ISCO 6500 or American Sigma automatic water sampler with the intake placed as close as possible to the turbidimeter. Suspended sediment concentration was determined in the field by vacuum-filtering samples of a known volume (typically 150 ml) through pre-weighed and pre-dried quantitative Whatman 40 (8 μm) Ashless filters, drying in desiccators for 24 h before re-weighing and calculating the concentration. The high suspended sediment concentrations present in the proglacial streams precluded the use of a standard, 0.45 μm pore size filter due to extended filtering and drying times. Loss of fines due to the greater pore size of the Whatman 40 filter papers was likely minimal as the effective pore size was rapidly reduced by clogging. A lack of observable sediment in the filtrate further indicated that minimal fine sediment was being lost although it was not possible to quantify this. The retention size of the Whatman 40 filters, therefore, allows for fast filtration and rapid field processing of a large number of samples with minimal loss of the fine fraction from each suspended sediment sample (Gurnell et al., 1992a). The water sampler concentrations were then compared to the concurrent reading of the turbidimeter. Each calibration was based on between ~50 and 100 samples over the natural range of turbidity. The resulting calibration equations were then used to convert the turbidity signals to suspended sediment concentration estimates.

### 4.4. Results

None of the turbidimeters were damaged during the 9 weeks of the field season, yielding almost continuous records of turbidity. Seven of the eight HOBS showed a linear response to changes in suspended sediment concentration over the full range of suspended concentrations observed in the field (two representative examples are shown in Fig. 7). Instruments 1 and 2 gave linear calibrations for sediment concentration ranges of ~0–500 and 0–1600 mg $L^{-1}$, respectively, with explained variances of 82.5% and 75.7%. Both instruments showed an increase in scatter compared to the laboratory-determined relationship for the same concentration range. This was not unexpected as field calibrations are seldom as precise due to increased error in measurement of suspended sediment concentration under field conditions and natural variability in suspended sediment size affecting turbidity measurement (e.g., Gurnell et al., 1992b). Instrument 3 showed a non-linear calibration over a wide suspended sediment range (0 to 10,000 mg $L^{-1}$) but the response still yielded an explained variance of 75.8%. The variability between each instrument highlights the need for field based calibration for each instrument and site.

## 5. Discussion

Successful in deployment and robust enough to withstand the rugged conditions of a proglacial environment, the HOBS turbidimeter was responsive to a suitably wide range of turbidity, sensitive to the dominant particle size in suspension, not affected by temperature fluctuations and had a predictable response to changes in concentration. In the laboratory, the HOBS calibration was statistically significant over a wide range of suspended sediment concentrations. The instrument was most sensitive to coarse clay and silt-sized fractions, but much less responsive to other particle sizes. This confirmed the HOBS suitability for use in proglacial streams where clay and silt are the dominant particles transported. In the field, the HOBS performed well over a wide range of suspended sediment concentrations, although the calibration curves differed between individual units. The necessity for site-specific calibrations may arise from differences in sediment composition and size distribution over the measurement period and from errors in sampling and determination of suspended sediment concentration (e.g., Richards, 1984; Fenn and Gomez, 1989; Gippel, 1989; Gurnell et al. 1992a). Such differences emphasize the need to establish the relationship between turbidity and suspended sediment concentration for individual instruments in the field.

Although field calibration gave acceptable correlations, the range of sediment concentration affected the linearity of the HOBS response. Responses were linear up to ~2000 mg $L^{-1}$ but non-linear when large ranges were encountered (in the order of 2000 to 10,000 mg $L^{-1}$). Other authors have also found systematic, non-linear calibrations at similar ranges (e.g., Ludwig and Hanes, 1990; Clifford et al., 1995a; Brasington and Richards, 2000). Although operation over the full range of suspended sediment concentrations encountered in the field is desirable, sensitivity at very low and very high concentrations may be reduced if the range is large (Gippel, 1989; Brasington and Richards, 2000). This change in sensitivity may be accounted for by changes in particle size under different flow conditions. For example, an increase in sand size particles under higher discharge would result in a reduced signal from the HOBS relative to an apparent increase in suspended sediment concentration due to the increased mass. Natural variability in particle size affecting the turbidity signal in the field may also explain the reduced slopes of the laboratory calibrations compared to the field calibrations. Despite these problems, the wide dynamic range of the HOBS is a distinct advantage when measuring the large fluctuations of suspended sediment characteristic of proglacial streams.

Suspended sediment concentrations are used in a wide range of disciplines to establish impacts of natural processes and human activity. Although the field calibrations of the HOBS were less precise than the laboratory calibrations, the instrument nevertheless provides a good basis for monitoring changes in suspended sediment patterns in proglacial streams (Orwin and Smart, 2004a). The good performance of the HOBS in this environment and its simple design means that it may have potential applications in other fluvial environments, particularly where a spatial component is desirable. Using this design, networks of turbidimeters can be established relatively inexpensively as one HOBS can be built for a total cost of ~US$300 (2002 prices). Modification of the gain setting and/or wavelength depending on the end use would increase the HOBS versatility. This would result in better characterization of both the temporal and spatial patterns of suspended sediment mobilization within a given landscape.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.geomorph.2004.04.007.

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