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Reliability and representativeness of a suspended sediment concentration monitoring programme for a remote alpine proglacial river

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ABSTRACT This paper considers the reliability and representativeness of a suspended sediment time series estimated for the proglacial stream of the Haut Glacier d'Arolla, Switzerland. In particular it considers the degree to which a continuous turbidity record can be used to estimate suspended sediment concentration under rigorous field conditions and powered by batteries and solar energy as a substitute for hand or pumped water sampling; the comparability of suspended sediment concentrations determined from filtration of meltwater sampled by automatic pump sampling and by hand sampling; the influence on the determinations of the chosen, fast-filtration filter paper in comparison with a control of samples filtered using high-retention, cellulose nitrate papers; and the degree to which suspended sediment is mixed in the river cross section and thus is adequately represented by a record for a single fixed point.

INTRODUCTION

Although the degree of quality control expected of a laboratory investigation cannot be achieved under field conditions, it is both possible and necessary to evaluate the instrumental, procedural and sampling techniques that are implemented in field investigations. Studies of suspended sediment concentration in proglacial rivers by the authors (eg Bezinge et al, 1988; Gurnell and Warburton, 1990) have increasingly depended on the calibration and interpretation of turbidity records. This reliance has been possible because studies have been undertaken in glacier basins which form part of a hydro power scheme operated by Grande Dixence S.A. in southern Switzerland. With the co-operation of Grande Dixence, it has been possible to locate turbidity meters within the hydro-power, water-intake installations. This has provided instrumentation sites which are close to the glacier and which are effectively monitoring the proglacial stream and yet they are near a mains electricity supply and are in the completely dark tunnels, through which the rivers are diverted. In these circumstances, turbidity records have been found to provide a reliable means of continuously monitoring suspended sediment concentration with only a limited requirement for filtration of calibration water samples and for routine cleaning of the turbidity probe.

In the course of an integrated study of the glaciohydrology of a high level alpine glacier basin (Haut Glacier d'Arolla, Valais, Switzerland), both turbidity and pumped sampler monitoring techniques were used to estimate a suspended sediment concentration time series for the proglacial river over two ablation seasons. The remote nature of the basin and the requirement for monitoring close to the glacier snout necessitated powering the instruments from batteries and solar panels (a power source that is likely to be less stable and reliable than mains electricity supply) and mounting the instruments on the bank of the river. It was also essential that filtration of water samples could be undertaken rapidly and efficiently in the field. This paper considers the reliability and representativeness of the estimated suspended sediment concentration time series. In particular, it addresses the following four specific aspects of the study:-

(a) The degree to which a continuous turbidity record (from a Partech 7000 series, model 3RP suspended solids monitor with a single gap SDM-10 probe) can be used to estimate suspended sediment concentration under these rigorous field conditions using battery/solar power.

(b) The comparability of suspended sediment concentration determined from filtration of meltwater sampled by an ISCO automatic pump sampler and by USDH48 hand sampling at the same location.

(c) The influence of the chosen, fast-filtration (Whatman 40, 8 μm retention) filter paper in comparison with a control of samples filtered using cellulose nitrate (Millipore 0.45 μm retention) papers on the resulting suspended sediment concentration estimates.

(d) The degree to which suspended sediment is mixed across cross sections in such a turbulent and fast flowing proglacial river and thus is adequately sampled at a single fixed point.

THE DEGREE TO WHICH A CONTINUOUS TURBIDITY RECORD CAN BE USED TO ESTIMATE SUSPENDED SEDIMENT CONCENTRATION

Figure 1 plots the joint observations of turbidity and suspended sediment concentration obtained using a Partech 7000 model 3RP suspended sediment monitor with single gap probe and filtration of water samples taken using a USDH48 sampler and filtering through Whatman 40 filter papers. These data were collected in 1986 within a hydro-power intake which diverts the proglacial river of the Glacier de Tsidjiore Nouve, and illustrate the effectiveness of using a turbidity meter to continuously monitor suspended sediment concentration in a location which is free from ambient light and which possesses a stable power supply. A calibration curve estimated from these data using simple linear regression analysis gave an R^2 of 0.964 and a standard error of the estimate of 144 $mg.l^{-1}$. Figure 1 thus shows the quality of calibration for suspended sediment concentration that we might expect to obtain under 'ideal' turbidity monitoring conditions. The use of the USDH48 to calibrate the turbidity record is based on the assumption that this instrument, which is specifically designed for the purpose of sampling suspended sediment in rivers, should provide us with an estimate that is close to the true value, albeit for a single sampling site. Thus the remainder of this paper considers the data collected for the basin of the Haut Glacier d'Arolla and uses the quality of the relationship illustrated in Figure 1 and suspended sediment concentration determinations obtained using a USDH48 sampler as guides to the quality and reliability of these data. Whatman 40 filter papers were used in both the Tsidjiore Nouve and Haut Glacier d'Arolla studies to filter water samples. Since these filter papers were chosen for their fast filtration quality, it was also necessary to quantify both the degree to which suspended sediment was being lost as a result of the coarse retention capacity of the filters, and the influence of their hygroscopic properties on the estimated concentrations.

The basin of the Haut Glacier d'Arolla has an area of 11.7 km^2 of which 6.3 km^2 is covered by permanent snow and ice. It has an altitudinal range of 2560m at the glacier snout and suspended sediment monitoring station rising to 3838m at the highest point on the watershed. The valley train of the Haut Glacier d'Arolla consists of a significant proportion of sand- and silt-sized sediments and over much of this valley train only a thin veneer of sediment covers layers of buried ice. These features lead to a rather unstable proglacial river system which is subject to both sudden and gradual changes in the position, size and shape of the river channel. Within a short (<100m) distance of the glacier snout, individual tributary streams join to feed a single thread, relatively straight river channel. During the ablation seasons of 1989 and 1990, an automatic pump sampler and turbidity meter were mounted on the bank of this single-thread channel reach with the single gap turbidity probe and intake to the automatic pump sampler hose located some 2m out into the flow (approximately 25% of the channel width) and 15cm above the channel bed (approximately a third of the flow depth). These dimensions for the instrument locations are approximate because of the continually changing nature of the channel and the continually varying depth of water within the channel. Such difficult and variable channel and flow conditions provided a severe test for these instruments.

In both 1989 and 1990 water samples were collected by the pump sampler every 2h, although there were gaps in these records over some nights when the instrument was disabled by icing. A preliminary examination of the suspended sediment concentration and turbidity data (together with stage and conductivity records) showed that there were subtle changes in the interrelationship between variables through the ablation season (Gurnell et al, 1991). The total record for each ablation season was, therefore, split into five, hydrologically consistent subperiods in each year (although periods 1 and 2 in 1989 were pooled for analysis of the relationship between suspended sediment and turbidity), and further analyses of these data were confined to these subperiods. Table 1 lists the simple linear regression relationships estimated between suspended sediment concentration (determined from individual pumped water samples) and turbidity (the average of 10 second readings over the preceding 10 minutes) for these subperiods and illustrates that the degree to which the turbidity record is able to 'explain' the suspended sediment record is always less than for the 'ideal' data presented in Figure 1. Other variables were, therefore, included in an attempt to increase the level of explanation of suspended sediment concentration in each of the subperiods. The multiple regression relationship that was found to provide the highest explanation (R^2 adjusted for the degrees of freedom) of suspended sediment concentration, whilst including slope coefficients that were significantly different from zero ($P<0.01$), in each subperiod is also presented in Table 1.

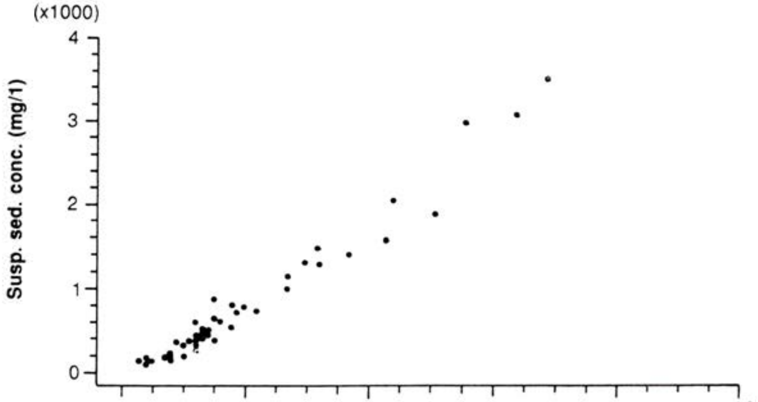

FIG. 1 The relationship between suspended sediment concentration established for the Glacier de Tsidjiore Nouve proglacial stream, 1986.

Figure 2 plots the suspended sediment concentration and turbidity time series for period 2 in 1990, illustrating a strength of relationship between the two variables that is comparable to that of the Tsidjiore Nouve data (Figure 1). However for the majority of the subperiods in Table 1 the relationship between the two variables is weaker (as represented by the R^2 values). There seems to be more inherent variability in these data than in determinations from hydro power intakes. However, some systematic reasons for the weaker relationships are indicated by the additional independent variables included in the multiple regression relationships for each period. In 1989, in particular, the varying influence of ambient light (or power supply as influenced by ambient light), turbulence and sediment particle size distribution on the turbidity record as water depth and discharge about the probe varied, may be indicated by the inclusion of either Q_t or Q_t in the multiple regression relationships.

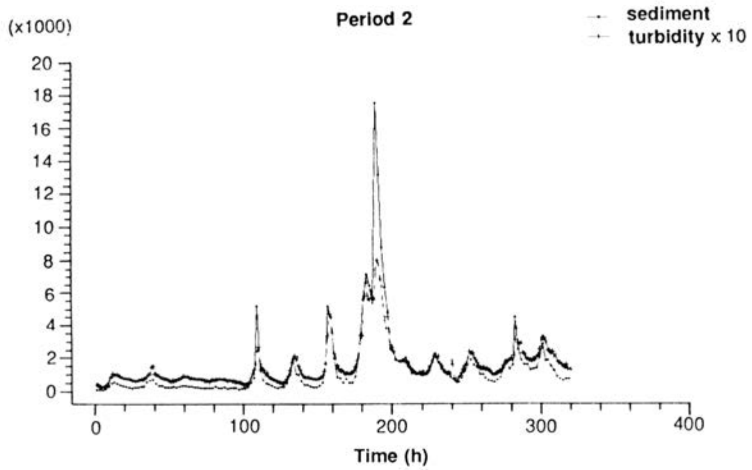

FIG. 2 Suspended sediment concentration and turbidity time series, period 2, 1990.

Such factors do not appear to be a significant problem in 1990, probably as a result of slight changes in the positioning of the probe or powering of the instrument. However, there is evidence of a linear temporal trend in the data in period 1, which could be the result of a reduction in the influence of ambient light as both the sediment concentration and discharge gradually increase through this period. Nevertheless, in all these cases of inclusion of significant additional variables, the increase in explanation of suspended sediment concentration is relatively small. In addition, the interactions between the possible causal factors are complex and require further investigation before their exact role can be unravelled.

THE COMPARABILITY OF SUSPENDED SEDIMENT CONCENTRATION DETERMINED BY FILTRATION OF MELTWATER SAMPLES FROM AN AUTOMATIC PUMP SAMPLER AND HAND SAMPLER

In the preceding section, estimates of suspended sediment concentration derived from filtration of water samples from an ISCO pump sampler through Whatman 40 (8 μm retention) filter papers have been used to calibrate continuous turbidity records. It is now necessary to assess whether the ISCO sampler and filter paper introduce significant errors in comparison with the datum of using a USDH48 hand sampler and Whatman cellulose nitrate 0.45 μm retention filter papers.

Figure 3 compares suspended sediment concentrations from concurrent samples taken over the 1989 and 1990 ablation seasons. In each case the USDH48 was placed next to the ISCO intake hose and was filled as the ISCO was also sampling. Although there is considerable scatter

TABLE 1 Estimated relationships between suspended sediment concentration and turbidity for subperiods of the 1989 and 1990 ablation seasons.

1989	
Periods 1 and 2: 01.00h 1 June - 21.00h 16 June	
$S = 4.75\ T + 131.09$	$R^2 = 0.603$
$S = 3.73\ T + 2.37\ Q_t - 226.62$	$R^2 = 0.640$
Period 3: 22.00h 16 June - 15.00h 8 July	
$S = 10.11\ T - 422.36$	$R^2 = 0.945$
$S = 10.14\ T + 0.49\ Q_t - 429.63$	$R^2 = 0.959$
Period 4: 16.00h 8 June - 24.00h 6 August	
$S = 11.75\ T + 492.99$	$R^2 = 0.700$
$S = 9.87\ T + 0.20\ Q_t - 957.21$	$R^2 = 0.733$
Period 5: 01.00h 7 August - 24.00h 31 August	
$S = 12.21\ T - 514.84$	$R^2 = 0.792$
$S = 8.54\ T + 0.29\ Q_t - 885.30$	$R^2 = 0.834$
1990	
Period 1: 16.00h 29 May - 07.00h 19 June	
$S = 6.57\ T - 169.0$	$R^2 = 0.762$
$S = 6.61\ T - 0.20\ \text{count} - 122.0$	$R^2 = 0.850$
Period 2: 08.00h 19 June - 15.00h 2 July	
$S = 15.16\ T - 1020.9$	$R^2 = 0.875$
$\log_{10} S = 1.646 \log_{10} T - 0.596$	$R^2 = 0.938$
Period 3: 16.00h 2 July - 17.00h 27 July	
$S = 11.64\ T - 315.6$	$R^2 = 0.843$
Period 4: 18.00h 27 July - 11.00h 13 August	
$S = 11.37\ T - 203.8$	$R^2 = 0.830$
Period 5: 12.00h 13 August - 10.00h 26 August	
$S = 10.68\ T - 4.5$	$R^2 = 0.745$

All slope coefficients are significantly different from zero ($P<0.01$). R^2 values are adjusted for the degrees of freedom of the estimated model. S - suspended sediment concentration in $mg.l^{-1}$, T - turbidity as a deflection across an arbitrary scale fixed at the start of the season, Q_t - concurrent discharge in $l.s^{-1}$, Q_t - change in discharge over the preceding hour in $l.s^{-1}$, count - number of hours since start of period. Periods 3, 4 and 5 1990 produced no improved regression relationship over the simple linear regression equation presented.

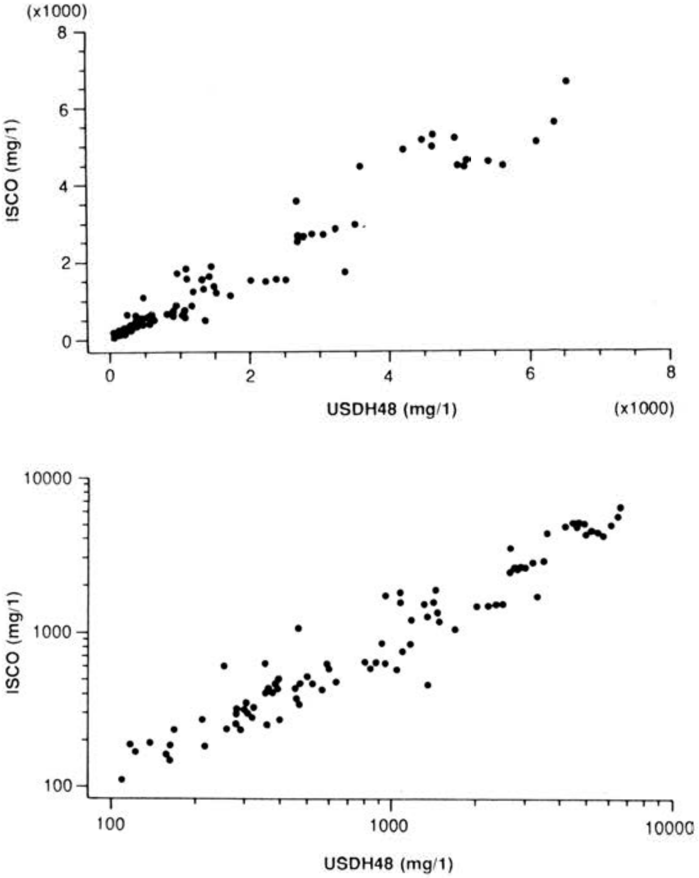

FIG. 3 Suspended sediment concentrations determined from water samples taken concurrently by ISCO and USDH48 samplers.

in the data, a clear positive trend is evident and a simple linear regression relationship estimated with the ISCO determinations as the dependent variable is as follows:

$$\underset{}{\text{ISCO}} = \underset{(15.05)}{1.20}\ \text{USDH48} - \underset{(0.30)}{19.67} \qquad R^2 = 0.822,\ n = 51,\ \text{t statistics in brackets, standard error of the estimate} = 291.0\ \text{mg.l}^{-1}.$$

Thus the intercept is not significantly different from zero and a hypothesis that the slope is 1.0 is only just rejected (standard error of the slope = 0.08). The regression relationship was re-estimated after a logarithmic transformation of the axes (Figure 3) to produce a more even distribution of the determinations and a more homoscedastic distribution in the residuals from the estimated regression relationship. This resulted in a slope estimate of 1.07, which, with a standard error of 0.07, was not significantly different from 1.0. These results suggest that the ISCO sampler is providing unbiased estimates of suspended sediment concentration in comparison with the USDH48 sampler, although the variability in the estimates from the ISCO in comparison with the USDH48 is high (as illustrated by the standard error of the estimate of the untransformed regression relationship).

THE INFLUENCE OF THE CHOSEN FILTER PAPER ON ESTIMATES OF SUSPENDED SEDIMENT CONCENTRATION

In the analyses presented so far, all of the water samples were filtered through Whatman 40 (8 µm retention) filter papers. These filter papers were chosen because they were relatively inexpensive and provided a medium for fast filtration. Speed of filtration was very important because the large number of samples were all filtered in the field using a hand pump to induce filtration. However, to offset the logistical advantages of Whatman 40 papers, there are two disadvantages. The first is the coarse retention size and the second is that the papers are hygroscopic. Since the papers are ashless, the latter problem could be overcome by igniting the papers prior to weighing the retained sediment. However, it is simpler to weigh, filter and reweigh the papers, so laboratory procedures were developed to minimise any weight change resulting from moisture absorption.

Figure 4 plots the proportion of total suspended sediment concentration lost by filtering samples from the ISCO and USDH48 through Whatman 40 rather than cellulose nitrate (0.45 µm retention) filter papers. There appears to be no difference in loss according to the water sampler used but the proportion lost increases greatly below suspended sediment concentrations of 1000 mg.l^{-1}. Above this threshold the loss is about 1% of the total suspended sediment, but below the threshold this rises to approximately 4% at 400 mg.l^{-1}.

Figure 5 shows the result of an experiment where 100 Whatman 40 filter papers were oven dried for at least 1 hour, were then placed in a desiccator in batches of 20 and reweighed in a fixed sequence. The papers were then wetted, redried and reweighed in the same sequence using the same batches of 20 papers and using the desiccator to store each batch prior to reweighing. Figure 5A shows the absolute weight change recorded (-5 to +1.5 mg) and Figure 5B shows the weight change adjusted by a linear correction based on the weight change of the 20th paper in each batch (standard deviation = 1.1 mg). Since water samples in this study had a volume of around 0.4 l, this adjusted weight change translates into an error of +/- 2.8 mg.l^{-1} ($P<0.05$).

THE DEGREE TO WHICH SUSPENDED SEDIMENT IS MIXED ACROSS THE RIVER CROSS SECTION

During July 1990, depth integrated water samples, velocity and water depth observations were obtained for cross sections of the Haut Glacier d'Arolla proglacial stream. The extremely high water velocities encountered in the section at the suspended sediment monitoring site precluded such data collection at that site. Not only was it dangerous to wade the section, but it was extremely difficult to use the current meter and USDH48 sampler with any precision in this section. Instead, three sections across the main tributary stream draining the glacier, which contributed the majority of the flow to the sediment monitoring section, were studied. Figure 6 illustrates observations taken on the three sections on 3 July 1990. Such observations were collected on four different days and showed that once the location within the cross profile was beyond any shallow water close to the banks, there was little evidence of any consistent systematic variation in suspended sediment concentration across any of the sections, even when there were very marked changes in flow velocity. In Figure 6, for example, section A shows a gradual rise in suspended sediment concentration across the stream, but this was not evident on other occasions; sections B and C exhibit apparently random variations around an average suspended sediment concentration level. The degree of (random) spatial variability can be illustrated by expressing the standard deviation as a proportion of the mean for each of the three cross sections and four sampling occasions. The values of this ratio ranged from 0.176 to 0.592, with a mean of 0.339 and with very variable values of the ratio between days and between sections. These results imply that the sediment is well mixed across the flow and that although

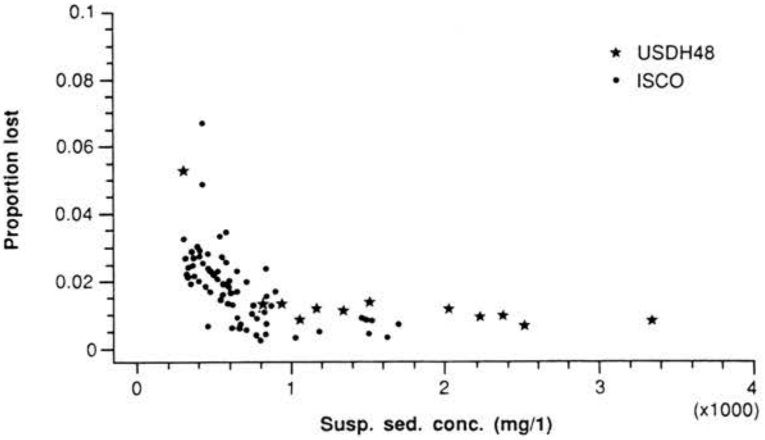

FIG. 4 Proportion of total suspended sediment lost by filtration though Whatman 40 filter papers; water samples from ISCO ( ) and USDH48 (*) samplers.

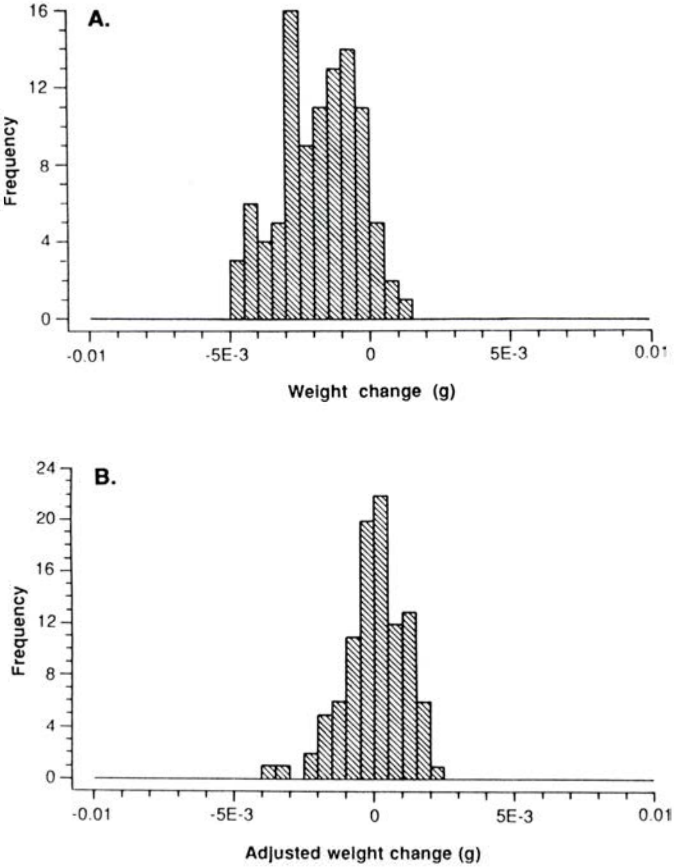

FIG. 5 A. Weight change in Whatman 40 papers as a result of drying, wetting and redrying. B. Weight change after linear correction for change in weight of every twentieth paper.

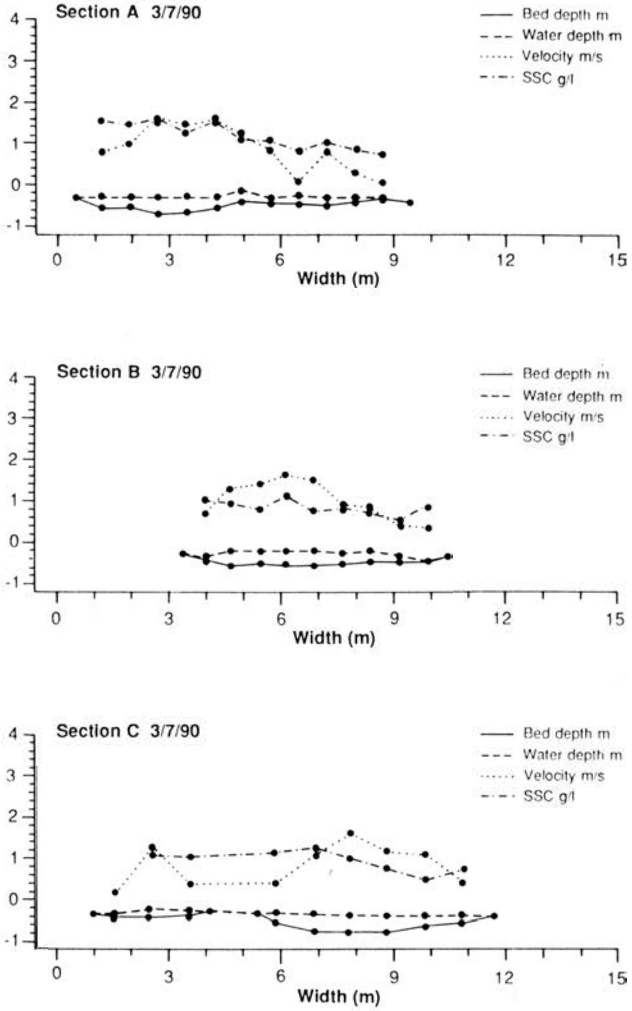

FIG. 6 Variations in suspended sediment concentration, velocity and water depth across three river cross sections.

suspended sediment concentration may vary from point to point, this variation, once away from the river banks, is essentially random and, therefore, sampling at any one location should give an unbiased estimate of section suspended sediment concentration.

CONCLUSIONS

The analyses presented in this paper have shown:

(a) that although a turbidity meter located in the harsh environment of the Haut Glacier d'Arolla and powered by batteries recharged by solar energy does not provide turbidity records with as high an explanation of variations in suspended sediment concentration as reported in previous studies under 'ideal' conditions by the same authors, it nevertheless provides a very good basis for interpolating between determinations using other instruments. Indeed, given the inherent variability in suspended sediment concentration in the study river (see (c) below), and the integrating effect of using the average of 10 second turbidity observations over 10 minute periods, it is possible that the weaker relationships between these two variables are as much a function of suspended sediment concentration variations over short time periods and short distances (between sampler intake nozzle and turbidity probe) as they are a function of any inadequacies in the reliability of the turbidity record.

(b) that the errors resulting from the use of different filter papers is small and can be accommodated and corrected by good field and laboratory practice.

(c) that different instruments used to estimate suspended sediment concentration can be intercalibrated and that although some imprecision in the intercalibration can be explained by instrumental inadequacies, much of it is probably a result of the inherently high spatial variability of suspended sediment concentration across river cross sections, between cross sections, and even at a single point within the section (as illustrated by concurrent determinations from USDH48 and ISCO samplers, Figure 3). Since much of this variability appears to be random, there is little improvement that can be made in monitoring suspended sediment concentration apart from ensuring that when different instruments are used in combination, they are carefully cross-calibrated to avoid the introduction of any systematic errors into the combined estimates.

Thus the analyses reported here justify the use of carefully controlled investigative techniques under quite extreme field conditions. There is a strong implication, however, that fully-documented calibration and evaluation of instruments, procedures and sampling design should be regarded as an essential component of any such study and of any associated publications.

ACKNOWLEDGEMENTS

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