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The Use of A Laser Light-Scattering Technique in Fluvial Sediment Measurement

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RINGKASAN

Kertas ini melapurkan pengukuran yang dibuat ke atas kepadatan enapan dengan menggunakan teknik penyerakan-cahaya laser. Dalam bentuk yang sedia ada, teknik ini mengalami beberapa masalah praktik, tetapi sifat yang mudah dan cepat membuatkan teknik ini lebih berguna. Cara-cara untuk mengatasi masalah-masalah yang timbul turut dibincangkan.

SUMMARY

In this paper, we report the measurement of sediment concentration using a laser light-scattering technique. In its present form, the technique suffers from several practical limitations but these are outweighed by the simplicity and speed of the technique. The procedures used in overcoming the accompanying problems are discussed.

INTRODUCTION

The amount of sediment transported in streams and rivers can serve as a hydrological indicator in the study of erosion, flooding, silting, etc. Measurement of sediment transported in suspension has therefore become a crucial part of routine hydrological investigations and of process study in hydrology. Other important studies include surface run-off investigations and geomorphology.

Measurement of suspended sediment involves two stages, the sampling of a portion of stream-flow, and the determination of the concentration of sediment in the sampled volume of water. Traditional analytical methods of sediment-concentration measurement involve operations such as decanting, filtering and weighing. Although these procedures are straight-forward, they are time-consuming. Through development of new techniques, a search is being conducted for an analysis that is more efficient. The search has included studies of response of sediment-water suspensions to various form of radiant energy, to electrical currents and to applied forces.

Sediment particles interact with radiant energy to produce both scattering and absorption. Acoustic interactions were investigated by Flammer (1962) who showed that the attenuation of energy was affected by both particle size and concentration. But many problems have hampered the application of the technique, such as drift-limited sensitivity and interference from small amounts of air.

Brown and Ritter (1971) measured the sediment concentration using an optical method. The method, although sensitive to sediment concentration as low as a few milligrams per litre, is subject to large random errors. This is because the intensity and spatial distribution of scattered flux is a function of the indices of refraction of the fluid and particles that vary with time.

A gamma-ray type of sediment gauge was designed by Ziegler, Papadopoulous and Sellers (1967) for battery operation at remote unattended sites. But, because of excessive drifts, high failure rates, high maintenance costs and high assembly and installation costs, the system was abandoned.

Sediment concentration and particle size measurement employing the electrical conductivity principle has been shown to be extremely accurate. In the Coulter Counter (USIACWR, 1964), the electric field is confined by an insulated orifice

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that bounds a volume of liquid of the same order of magnitude as the volume of a single sediment particle. The confined field enables the instrument to count and size individual particles as they are drawn through the field. Because fluvial sediment particles have a wide range of sizes, the orifice frequently plugs. However, Killen (1969) eliminated the plugging problem by using orifices much larger than that used in the Coulter Counter. He also employed a device consisting of two orifices electrically connected in a bridge measurement. The system includes a hydrocyclone separator that diverts sediment to one leg of the bridge and relatively clear reference water to the other leg.

Beverage and Skinner (1974), constructed a special hydrometer that responds to small differences in density. The mixture is placed inside the hydrometer, which is then submerged in a water bath. The bath water which is free of sediment, serves as density reference. Temperature sensitivity proves to be the largest source of error. With temperature variation limited to ± 0.5° C, the concentration can be measured, but only with an uncertainty of ± 50 $kg.m^{-3}$.

The principle of light scattering has in the past received much attention as a means of measuring the concentration, size and shape of suspended particulate matter. In a system developed by Bickel (1979), a laser beam from a fixed external source that is in a definite and exactly known polarization state enters a scattering chamber mounted on a rotating table. The scattered light is detected and analyzed by fixed analyzing optics and detector, as the table rotates through 360°. The laser beam is aligned along the axis of rotation and prepared into a well-defined polarization state by several optical components mounted on the table. The system of Diehl *et al.* (1979) makes use of six detectors mounted around a sample at angles of ± 45°, ± 90° and ± 135° from the incidence laser beam to study particulate contaminants in a sample of suspended solids. The scattered signals are analyzed by examining the pulse heights from these detectors simultaneously. The pulse heights are stored in a computer. The method has application in optical categorization of samples for remote sensing purposes.

The techniques of light-scattering mentioned above are examples of two out of the many techniques (references to other methods can be found in Diehl *et al.* (1979), Bickel (1979)) which depend principally on the properties of the scattered beam of which considerable work, both theoretically and experimentally, has been carried out in the past (see for instance, Spinrad *et al.* (1978) and the references quoted there in). Although many properties of the scatterer may be studied using this principle, the resulting system usually requires elaborate optical arrangements and/or several detectors, and is often cumbersome. In this paper, we report on the results of several measurements of sediment concentration using a laser-light scattering device originally designed by Woolsey and Douglas (1979). Since the method uses the principle of attenuation of electromagnetic waves by a scattering medium, the number of optical components required are small. However, as with other light-scattering techniques (Diehl *et al.* (1979), Bickel (1979)), the concentration is equally sensitive t the size of the particles. We have therefore restricted our investigations to particles having diameter, d, in the following ranges; $d \leqslant 50\ \mu m$, $50\ \mu m \leqslant d \leqslant 100\ \mu m$ and $100\ \mu m \leqslant d \leqslant 150\ \mu m$.

In the next section we describe the principle of the method employed in this work. In the section on the procedure and results, we establish the correspondence between the laser scattering data and filter data. Finally, we show how the laser method is applied to determine the absolute concentration of the above-mentioned particles. Since the concentration can only be reliably measured if multiple scattering is insignificant, the effect of multiple scattering on the measurements will be discussed in the section on procedure and results.

PRINCIPLE OF THE METHOD

When light passes through a medium containing suspended sediment, its intensity decreases as a result of scattering and absorption. True absorption represents the transfer of electromagnetic energy to the molecules of the absorbing material.

On a macroscopic scale, the interaction of light in a medium is described by Lambert's law. According to this law, equal fractions of light intensity are lost when the light traverses equal lengths of the medium. The behaviour can be summarized neatly by the well-known exponential expression,

$$I = I_0\, e^{-kx} \qquad \ldots (1)$$

where I is the intensity of the light after traversing a distance x, I_0 is its original intensity and k is the absorption constant, characteristic of the medium and is physically associated with the cross-section for collision. In the case of two light beams passing through the arrangement depicted

in *Fig. 1*, straightforward extension of equation (1) shows that

$$k = \frac{1}{(d_2 - d_1)} \ln\left[\frac{I_1}{I_2}\right] + C \qquad \ldots (2)$$

where C is a constant that depends on the intensities of the incident beams.

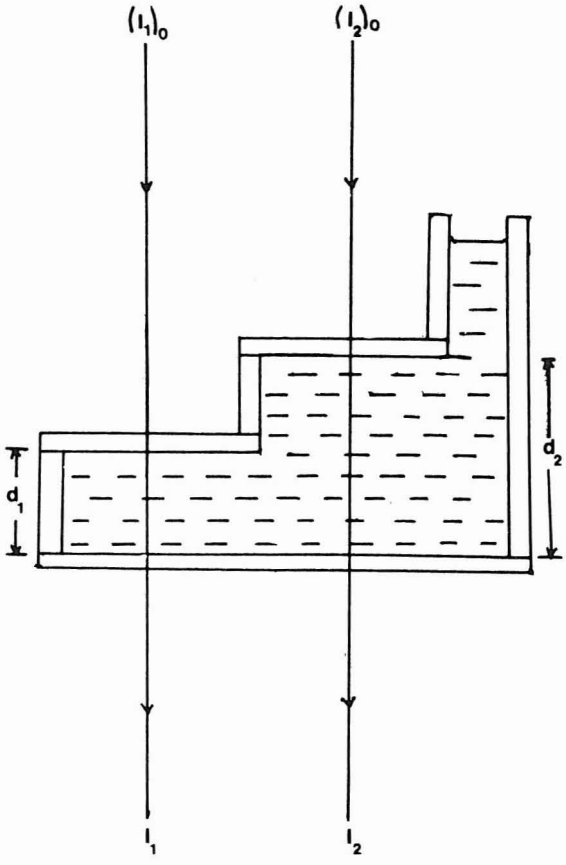

Fig. 1. Sample cell showing incident and transmitted beams (volume of cell : 1.35 × 10^{-4} m^3).

If the particles are assumed to be spherical with radius r and their number per unit volume is N, then

$$k = N\pi r^2 \qquad \ldots (3)$$

This can be shown as follows. Let A be any arbitrary cross-sectional area of the light path. Then, the probability of an interaction is $\frac{a}{A}$ where a is the cross-sectional area of a particle. The probability of no interaction and hence transmission is $\left[1 - \frac{a}{A}\right]$. If there are n particles in the light path, the probability of transmission is $P_T = \left[1 - \frac{a}{A}\right]^n$. Since $a \ll A$ and n is large, $\left[1 - \frac{a}{A}\right]^n$ may be written as $\exp\left[\frac{-na}{A}\right]$. Since N is the number of particles per unit volume, and x is the distance traversed, $N = n/Ax$. Thus, the probability of transmission $P_T = \exp(-N\alpha x)$. But the area $a = \pi r^2$ where r is the radius of the particle assumed spherical. Therefore, $P_T = \exp(-N\pi r^2 x)$ and hence $k = N\pi r^2$.

Since the mass of the sediment per unit volume is,

$$M = \frac{4}{3}\pi r^3 \rho N \qquad \ldots (4)$$

where ρ is the density of the particles,

$$k = \frac{3}{4}\frac{M}{r\rho} \qquad \ldots (5)$$

showing that k is directly proportional to the concentration M.

In practice, deviation from equation (5) is expected for the following reasons;

(i) the particles are not spherical and have varying sizes,

(ii) the particles do not have the same density, although their densities do not differ very much from each other,*

(iii) detailed analysis shows that the absorption process depends on the refractive indices of the particles,

(iv) Lambert's law is not obeyed at high concentration due to multiple scattering.

(v) heavier particles are not suspended but settle rapidly.

Despite these limitations, the laser scattering principle can still be applied to sediment, containing particles such as fine sand, silt or clay. Although these particles have a wide range of sizes, the use of a calibration curve derived from the same type of particles is generally sufficient and accurate enough to compensate for the deviations from the ideal situation.

* The specific gravity of the particles varies between 2.61 and 2.65.

Equating equations (2) and (5), relates the concentration to the light intensities, thus,

$$M = A \ ln \left[\frac{I_1}{I_2}\right] + C \qquad \ldots (6)$$

where

$$A = \frac{4r\rho}{3(d_2 - d_1)} \qquad \ldots (7)$$

PHOTODETECTING UNIT†

The relationship between the concentration and the light intensities of equation (6) is realized in the practical scheme of *Fig. 2*. Here, the transmitted beams I_1 and I_2 are first converted into electrical signals by the photodetectors. They are then passed through the logarithmic amplifiers, the outputs of which are connected to the differential amplifier. The outputs of the differential amplifier V is proportional to $log \left[\frac{I_1}{I_2}\right]$

The constant factor that appears in converting the logarithm to the base of 10 to natural logarithm is absorbed into a proportionality constant as will be explained later.

PROCEDURE AND RESULTS

The experimental arrangement is shown in *Fig. 3*. A polarized He-Ne laser of wavelength 632.8 nm acts as the light source. In an earlier attempt to develop the technique an unpolarized He-Ne laser was used. However, it was discovered that the detector output voltage showed cyclic variations. The behaviour was caused by axial mode switching as the laser cavity expanded longitudinally during the warm-up period after switch-on (Woolsey *et al.*, 1982).

The optical components consist of a beam-splitter, a prism and a front-surface mirror. The laser light is divided by the beam-splitter into two mutually perpendicular beams – a directly transmitted beam and a beam reflected at 90°. The transmitted light is allowed to fall on a reflecting mirror inclined at 45°. The latter reflects it into one of the two chambers of a sample cell *(Fig. 1)*. The depth of water in the two chambers is $d_1 = 3 \times 10^{-2}$ m and $d_2 = 7 \times 10^{-2}$ m. The reflected light of the beam-splitter is then totally reflected by a prism and continues to the inclined reflecting mirror. The mirror reflects it into the other chamber of the cell. The beams transmitted from the cell fall on the photodetecting unit of *Fig. 2*. The output of the photodetecting unit is registered with a millivoltmeter.

Muddy water samples were obtained from five different locations in the University campus. Before making each set of measurements the muddy water was throughly stirred and separated into suspensions of 500 ml in graduated cylinders. The suspended water was then quickly transferred to the sample cell after first mixing it thoroughly, and allowing it to settle for two minutes. The reading of the millivoltmeter was then recorded.

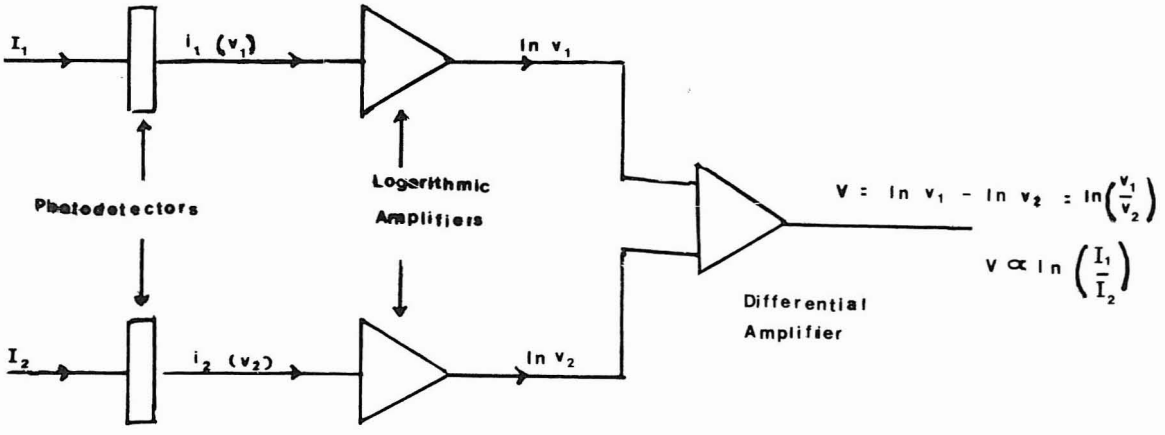

Fig. 2. Photodetecting unit.

† The photodetecting unit was constructed and assembled by the staff of the Physics Workshop, University of New England, Armidale, Australia.

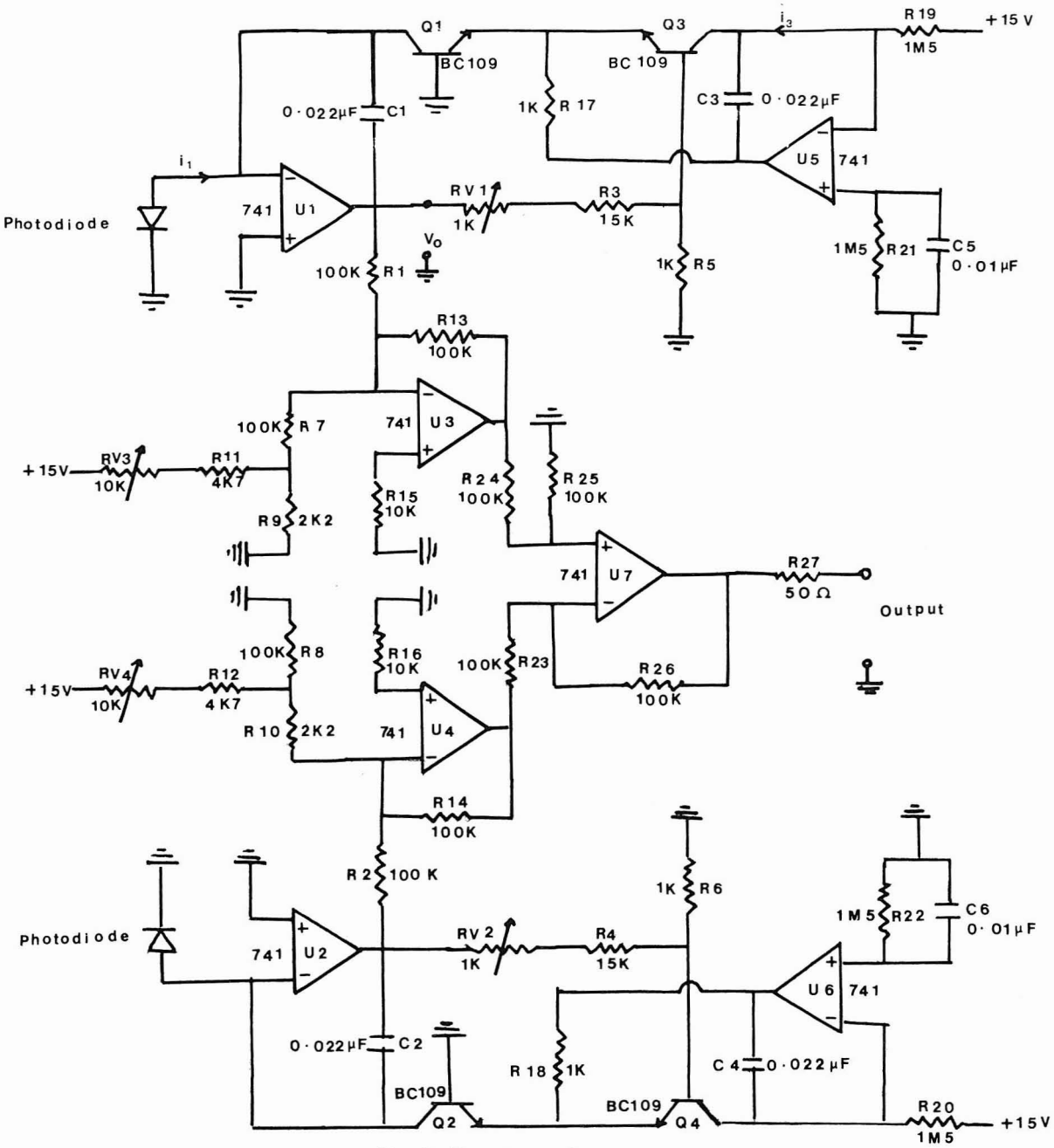

Fig. 3. Experimental arrangement.

The sample in the cell was then diluted by 10% (by volume) and the voltage re-measured. The procedure was repeated until the concentration of the final sample was 10% of the original suspension. *Fig. 4* illustrates the graph of voltage against relative concentration for this measurement. Other results can be found in Ali (1980). The voltage ($V-V_0$) in *Fig. 4* is the difference between the sample voltage and the reference voltage obtained with an equal volume of distilled water. The reference voltage was used to compensate for any drifts in the detecting system and this was periodically checked usually before, during and after a course of measurements of a set of samples.

In this part of the experiment, we have attempted to show the validity of equation (6)

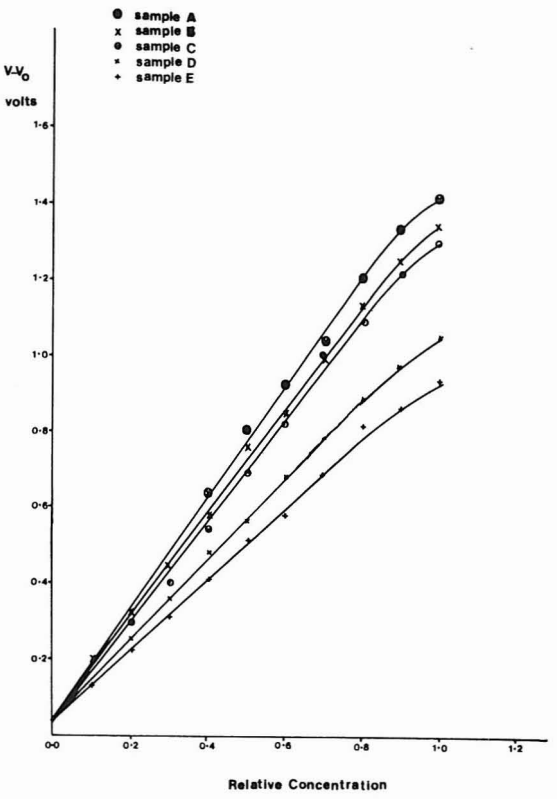

Fig. 4. Graph of $(V-V_o)$ against relative concentration of sediment.

and the problems that emerge at high concentration. According to equation (6), a plot of V (proportional to $ln\ \frac{I_1}{I_2}$) against M should be a straight line with a slope 1/A. As shown in *Fig. 4*, equation (6) is obeyed reasonably well at low concentration. The difference in the slopes of the curves can be attributed mainly to the difference in the particle size since the densities of the particles do not vary significantly. Thus the slopes serve to indicate that $r_A < r_B < r_C < r_D < r_E$ where r_X is the effective radius of the particles in sample X.

At high concentration, the curves are seen to deviate significantly from the straight line. This is due to multiple scattering for it has been shown (Spinrad *et al.*, (1979)) that when light interacts with particulate matter, more than half of the scattered radiant intensity is scattered at angles less than 3° from the incident beam. If the concentration and the size of the particles are large, this in effect causes the scattered beams to be redirected into the incident path thus effectively lowering the collision cross-section. Closer examination of *Fig. 4*, reveals the fact that for smaller r, the onset of multiple scattering occurs at a higher concentration than for larger r. Since equation (6) no longer holds in the presence of multiple scattering, high concentration samples must be diluted prior to any actual measurement. Our experience has shown that if the concentration is limited to less than 0.1 kg. m^{-3}, multiple scattering is insignificant for particles of size less than 160 μm in diameter.

The correspondence between these laser scattering data and filtering data is established by plotting a calibration curve. Since this is dependent on the particle size, we have chosen to work with particles having diameters in the following ranges: $d \leqslant 50\ \mu m$, $50\ \mu m \leqslant d \leqslant 100\ \mu m$ and $100\ \mu m \leqslant d \leqslant 150\ \mu m$. The categorization into these sizes is convenient as they correspond roughly to the size of clay, silt and fine sand respectively and their separation can be carried out by the methods of dry and wet sieving. These techniques are described in Ali (1980). Samples in each category were prepared by mixing some predetermined amount of the sediment (by weight) with a known volume of distilled water. The absolute concentration was made up so that the solution remained in the single-scattering region. About $1.35 \times 10^{-4}\ m^3$ of the suspension was then transferred into the measuring cell and the millivoltmeter reading recorded immediately. The suspended sediment in the cell was then filtered thoroughly and after constant drying, the weight determined. From the weight of the sediment and the volume of the filtrate, the absolute concentration of the sample was calculated and the average of the concentrations determined before and after laser measurement obtained. Meanwhile, the suspension that was left over from the first measurement was diluted by 10% (by volume) and the whole process of measuring and determining the average concentration repeated. The remaining data points were obtained in exactly the same way. *Fig. 5* shows the calibration curve for the three ranges of particle size.

The assumptions used in deriving equations (6), justifies one against equating the theoretical slope $S = \frac{1}{A}$ to the slope of the experimental curve directly. In addition, the conversion from ln_e to log_{10} involves a constant factor of 2.3 and the absorption cross-section may not be exactly equal to the sum of the physical sizes of the particles. This requires one to write,

$$S_{theory} = \kappa S_{expt} \qquad \ldots (8)$$

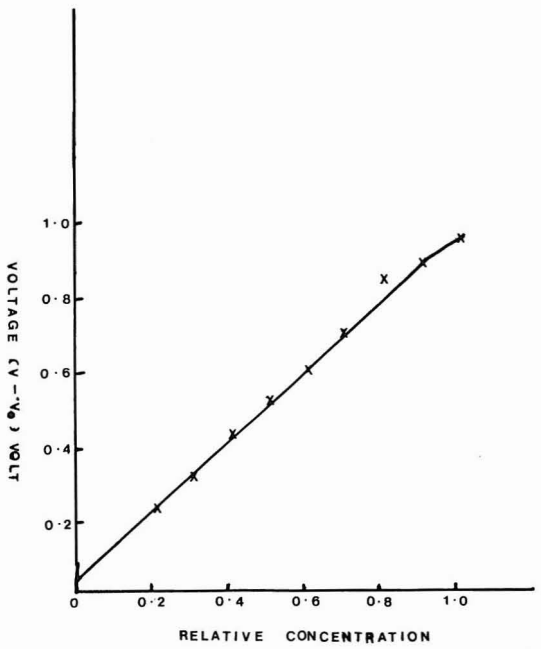

Fig. 5. Graph of $(V-V_o)$ against absolute sediment concentration for different particle sizes.

It remains now to find the value of κ. We have determined κ empirically in the following way. S_{expt} is evaluated using the calibration curves of *Fig. 5* for the different particle sizes. The values of S_{theory} are calculated from equation (7) for $r = r_{max}$ and $r = r_{min}$ in each particle size range, assuming a constant density for all the particles. Finally, the corresponding κ's are obtained from equation (8) and the average determined. The results of these calculations are shown in Table 1, where the average value of $\bar{\kappa}$ is found to be $(\bar{\kappa})_{ave} = 0.19$. Therefore,

$$S_{exp} \simeq 5\, S_{theory} \qquad \ldots (9)$$

This relationship enables one to use equation (6) to measure sediment concentration using the laser light-scattering technique. Ideally, any measurement that is made with respect to distilled water will help eliminate the constant factor C in equation (6) since for distilled water the particle concentration is naturally zero. Assuming, that this is approximately the case (as justified by the small intercept $\sim$ 4mV, in the graph of *Fig. 5*), then,

$$V-V_o = S_{expt}M \qquad \ldots (10)$$

where M is the concentration of sediment. From equations (9) and (10),

$$M = \frac{V - V_o}{5S_{theory}} \qquad \ldots (11)$$

If the particle size is known, then, S_{theory} can be calculated from equation (7) and M can be determined from equation (11). In a non-dispersive medium, samples of approximately known size may be obtained by using the settling method. This is the technique used to sample particle size according to their terminal velocity calculated from Stokes' equation. The terminal velocity varies with the size and the density of particles and also with the viscosity of the medium. The latter is a function of temperature. At 15° C, the terminal velocities for the 150,100 and 50 μm particles are calculated to be 1.8, 0.8 and 0.2 $\times$ 10^{-2} m. sec.$^{-1}$ respectively.

Alternatively, a calibration curve for the particle size of interest may be used directly to convert a measured $(V-V_o)$ value into an M value. Table 2 compares measurements of concentration made in this way with values obtained by filtering: agreement is obtained within 10%.

TABLE 1

Particle diameter μm	S_{expt} $m^3 kg^{-1}$	$(S_{theory})_{r_{max}}$ $m^3 kg^{-1}$	$(S_{theory})_{r_{min}}$ $m^3 kg^{-1}$	$\kappa_{r_{max}}$	$\kappa_{r_{min}}$	$\bar{\kappa}$
50	2.3	0.46	–	0.20	–	0.20
50 – 100	1.8	0.23	0.46	0.13	0.26	0.19
100 – 150	1.1	0.15	0.23	0.14	0.21	0.18

$(\bar{\kappa})_{ave} = 0.19$

The density of the particles is taken to be $2.63 \times 10^3 kg.m^{-3}$.

TABLE 2

Methods	Sediment concentration ($X10^{-1}$ kg m-3)				
Laser scattering	0.43	0.14	0.55	0.28	0.37
Filtering	0.40	0.13	0.54	0.27	0.40

CONCLUSION

We have shown how a laser light-scattering technique can be used to measure sediment concentration. However, before the method can be reliably applied, several considerations have to be taken into account. This is because of its dependence on several physical factors, notably the particle size. Nevertheless, because of its simplicity, low-cost and speed, the method offers an attractive alternative in sediment concentration measurement. Further work is currently being undertaken to improve the system.

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REFERENCES

ALI, M.J. (1980): Laser Scattering Measurement of Fluvial Sediment, B. Sc (Hons.) Project Report, Physics Department, U.P.M.

BEVERAGE, J.P. and SKINNER, J.V. (1970): Operator's Manual PS-69 Pumping Sampler. Federal Inter-Agency Sedimentation Project.

BICKEL, W.S. (1979): Optical System for Light-scattering Experiment. *App. Optics* **18**, 1707.

BROWN, W.M. and RITTER, J.R. (1971): Sediment Transport and Turbidity in the Eel River Basin, U.S. Geol. Survey Water-Supply Paper, 1986.

DIEHL, S.R., SMITH, D.T. and SYDOR, M (1979): Analysis of Suspended Solids by Single-Particle Scattering. *App. Optics* **18**, 1653.

FLAMMER, G.H. (1962): Ultrasonic Measurement of Suspended Sediment. U.S. Geol. *Survey Bull.* **1141-A.**

KILLEN, J.M. (1969): A Feasibility Study of a Field Instrument for the Measurement of Suspended-Sediment Concentration, Univ. of Minn., St. Anthony Falls Hydraulic Laboratory Project Report.

SPINRAD, R.W., ZANEVELD, J.R.V. and PAK, H (1978): Volume Scattering Function of Suspended Particulate Matter at Near-forward Angles: A Comparison of Experimental and Theoretical Values. *App. Optics* **17**, 1125.

USIACWR (1964): Electronic Sensing of Sediment, U.S. Inter-Agency Committee on Water Resources Report.

WOOLSEY, G.A. and DOUGLAS, 1 (1979): Measurement of Suspended-Sedimen Concentrations using a Laser Scattering Technique, 1st National Conference on Applied Physics (Australian Institute of Physics). Capricornia Institute of Advanced Education, Rockhampton.

WOOLSEY, G.A., SULAIMAN, M.Y. and MOKSIN, M (1982): Correlation of Changes in Laser Tube Temperature, Cavity Length and Beam Polarization For An Internal-Mirror Helium-Neon Laser. (accepted for publication in *Amer. J. Phys.)*

ZIEGLER, C.A., PAPADOPOULOS. J and SELLERS, B (1967): Radioisotope Gauge for Moniroting Suspended Sediment in Rivers and Streams. *Int. J. Applied Radiation and Isotopes,* **18.**

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