

SHORT COMMUNICATION

AN OPTICAL TACHOMETER FOR SHORT-PATH MEASUREMENT OF FLOW SPEEDS IN SHALLOW OVERLAND FLOWS: IMPROVED ALTERNATIVE TO DYE TIMING

DAVID L. DUNKERLEY*

School of Geography and Environmental Science, Monash University, Victoria 3800, Australia

Received 28 January 2002; Revised 10 June 2002; Accepted 27 July 2002

ABSTRACT

Tracers, such as fluorescein dye, are widely employed to measure overland flow speeds by time-of-travel along measured flow paths. Among several disadvantages of this method are the involvement of human reaction time when using stop-watches, and the relatively long travel path that is consequently needed for reliable timing. Long flow paths mean that local variability along the flow path cannot be detected.

This paper describes a new optical tachometer that overcomes these limitations, as well as offering other advantages. It is based on the use of a small floating reflector target that is carried on the surface tension film, and which passes between two reflective sensors mounted above the flow. The new device allows virtual 'spot' measurements of surface flow speed over a path as short as 1 cm, and eliminates the influence of human reaction time. The new device is battery powered and portable, and provides an improved alternative to dye timing in many field and laboratory applications. Its use will allow the collection of more refined data than have hitherto been easily achievable. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: flow speed; overland flow; travel time; surface velocity; optical tachometer

INTRODUCTION

The speed of overland flows is a key determinant of their competence to entrain and carry sediment. It is also a parameter required for characterizing the friction coefficient applicable to such a flow. Most experimenters in geomorphology and hydrology employ a tracer whose travel time across a marked course is determined using a stop-watch. A dye, such as fluorescein, is commonly used as a tracer, but, in the laboratory, salt solutions have also been used, with the passage of the tracer being followed using electrical conductivity probes or ion-selective electrodes (e.g. Barros and Colello, 2001). Others have employed more elaborate systems to track the advance of dye, such as the continuous pumping of part of the runoff through a fluorometer adopted in a field study by Gilley and Finkner (1991). Other kinds of velocimetry, such as particle image velocimetry (PIV), could be adapted to studies of overland flow. For example, PIV has been successfully used in beach swash studies (Holland *et al.*, 2001).

Surface flow speeds are used to estimate profile mean speeds using the relation $v = \alpha v_{\text{surf}}$, where v is the profile mean speed, v_{surf} is the surface speed and α is a coefficient. There is some evidence that, for laminar flow on granular surfaces like soils, the value α is nearer 0.56 than the theoretical smooth-surface value of 0.65 (Li *et al.*, 1996; Dunkerley, 2001).

* Correspondence to: David L. Dunkerley, School of Geography and Environmental Science, Monash University, Victoria 3800, Australia.
E-mail: david.dunkerley@arts.monash.edu.au

Difficulties associated with manual dye timing

The human reaction time, which can reach several hundred milliseconds (Welford, 1980), affects manual timing. Very short travel paths become challenging to time manually, requiring concentration and quick responses, so that flow paths of at least 0.25 m, but up to 6 m, are commonly adopted (Dunne and Dietrich, 1980; Roels, 1984; Abrahams *et al.*, 1986; Govers and Rauws, 1986; Guy *et al.*, 1990; Gilley and Finkner, 1991; Gilley *et al.*, 1992; Beuselinck *et al.*, 1999; Bryan and Brun, 1999; Nearing *et al.*, 1999; Rouhipour *et al.*, 1999). There appears to have been little testing to quantify the precision achieved when timing dye plumes. An exception is the laboratory flume study of Katz *et al.* (1995), in which, rather than a stop-watch, video recordings of a fluorescein dye plume were analysed in slow-motion, yielding speed data repeatable to within 5% (1 cm s^{-1}). For slow flows, shorter flow paths have been used successfully. For example, for flow speeds $< 10 \text{ cm s}^{-1}$, Fox and Bryan (1999) achieved quite small variances by timing across a distance of only 0.2 m.

The new optical tachometer was developed to allow flow speeds to be observed with precision over much shorter flow paths, allowing local speed variations on a test surface to be resolved.

A NEW OPTICAL TACHOMETER

The principle adopted is to detect optically the passage of a reflective target carried on the water surface. Once released on the water surface, the target is carried by the forces of surface tension, and passes sequentially beneath two optical detectors consisting of an infra-red light-emitting diode (LED) and a phototransistor. The particular devices used here (obtained from RS Components Ltd) consist of a diode and phototransistor packaged as a splash-resistant unit, with the diode and phototransistor aligned toward each other, to define a small region about 5 mm from the device where changes in reflectivity are sensed. Two identical diode–phototransistor sensors are mounted rigidly a short distance apart along the expected flow trajectory of the reflecting target. Passage of the target under the upstream sensor delivers a ‘start’ pulse to a stop-watch or other timing device (see below), and passage beneath the downstream sensor subsequently delivers a ‘stop’ pulse.

Targets and the ability of surface tension to support them

The reflective targets are made from common aluminium foil of the kind used for wrapping food. This weight of this material is about 4 mg cm^{-2} . Targets are circular in shape, to eliminate any effects of target rotation that might occur along the flow path, and which could alter the reliability of the timing process. Four target sizes were tested, having diameters of 5, 10, 20 and 25 mm. These were readily produced from foil sheet using a sharp-edged wad punch.

For water at room temperature the surface or interfacial tension γ is about 0.072 N m^{-1} , declining slowly at higher temperatures (Adamson and Gast, 1997). In effect, surface tension generates cohesion among molecules in a zone a few molecular diameters deep, which allows the water surface to support significant weights.

The disc-shaped tachometer targets had edge lengths of up to 7.85 cm and weights of up to 19.6 mg (Table I). However, the surface tension forces along these edges were capable of supporting loads 30–140 times greater than that of the target (Table I). Consequently, the targets were carried very buoyantly at the water surface.

Table I. Characteristics of the reflective aluminium targets used with the optical tachometer. Surface tension forces were calculated for pure water at the mean test temperature, and were not measured experimentally

Diameter (mm)	Weight (mg)	Edge length (mm)	Total surface tension force (N)	Ratio of total surface tension force to target weight
5	0.78	15.7	1.13×10^{-3}	144.4
10	3.14	31.4	2.26×10^{-3}	71.9
20	12.56	62.8	4.52×10^{-3}	35.9
25	19.63	78.5	5.65×10^{-3}	28.8

THE TACHOMETER: BRIEF TECHNICAL DESCRIPTION

The sensor assemblies

Three sensor assemblies were made, having the optical components separated by 10, 40 and 100 mm. The assembly consisted of a base plate with an optical sensor mounted at each end, and a central tubular handle suitable for attaching to a laboratory stand using a boss head clamp (Figure 1). The sensors are mounted at a non-critical height of about 1 cm above the water surface. A single multi-core cable carried the signals from each detector to the measuring electronics.

Control electronics needed to interface sensors to stop-watch

The detection circuitry is quite straightforward (Figure 2), and uses a combination of operational amplifiers for initial processing of the analogue signal from the optical sensors and some following digital logic to generate sharp pulses for controlling the timing device. Two identical sub-units are used to process the signals from the upstream and downstream sensors. The output from each phototransistor is AC-coupled to an amplifier providing a gain of 100. The capacitive coupling eliminates the effect of steady ambient illumination or slow changes of light intensity. The signal created by the passage of a reflective target is then filtered and rectified so that the circuit detects and responds to the passage of only one edge of the moving target, the trailing edge being selected. The circuit does not respond at all to the leading edge of a reflective target. Once detected, the transient signals caused by the target leaving the detector sensing area are shaped with Schmitt triggers, which employ hysteresis to sharpen the signal pulse, and latched using flip-flop circuits. The latched flip-flop outputs are then reduced to pulses of a few milliseconds duration using half-monostables, and finally passed to a two-input digital logic OR gate, whose single output swings high momentarily when either of the circuits is triggered by a

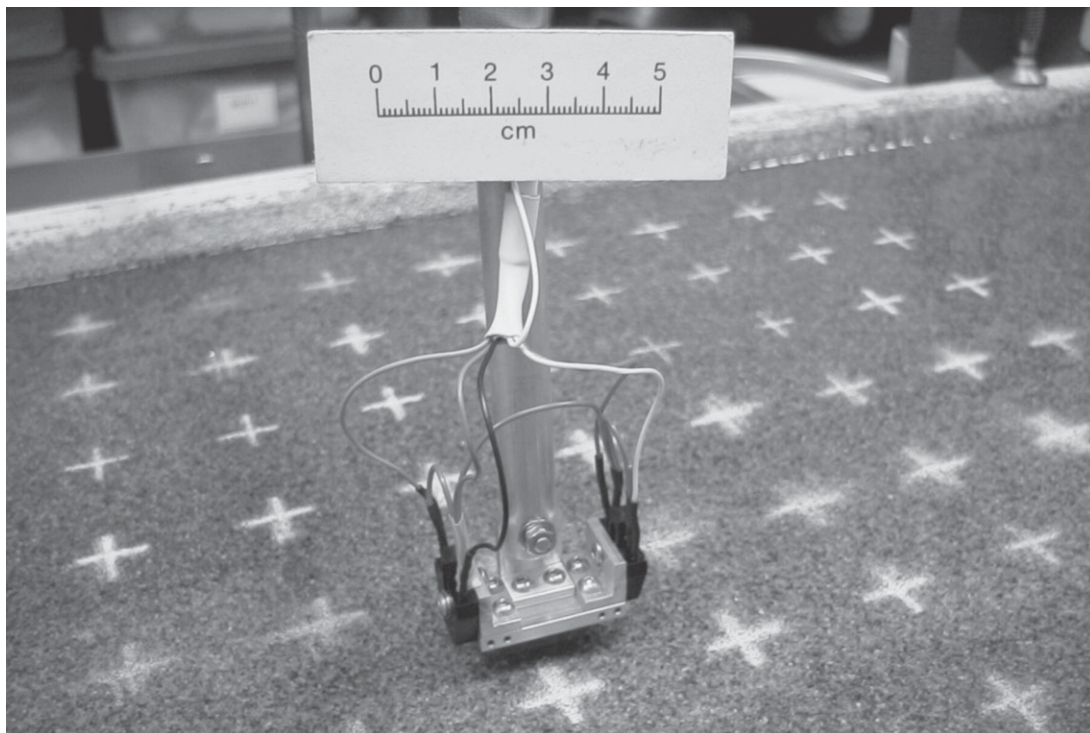


Figure 1. The 40 mm optical tachometer sensor. The black components mounted at each end of the sensor are the optical sensors. The device is mounted in operational position above the sand board used in testing. The grid of white painted crosses is used to locate obstacles in experiments on non-uniform flow

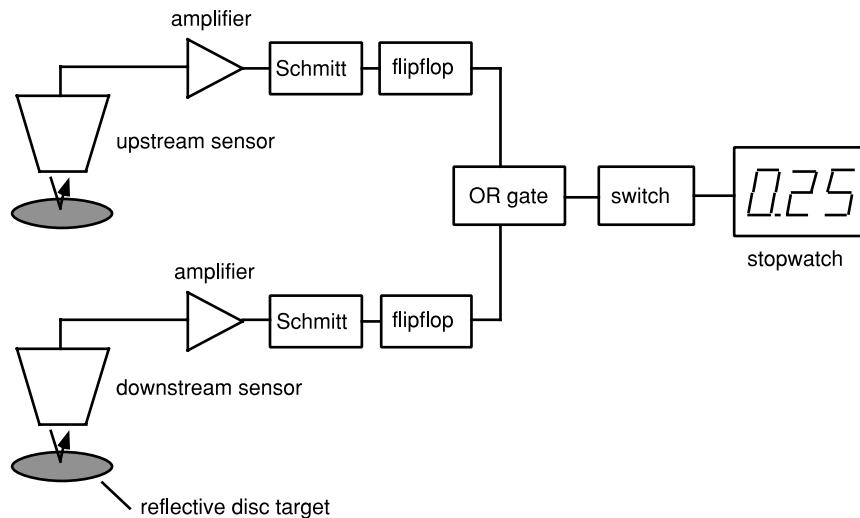


Figure 2. Schematic of the electronic circuit for the optical tachometer

reflective target. The OR gate activates a solid-state switch connected to the timing circuitry ordinarily triggered by the mechanical push buttons on the stop-watch. No voltages are present at the connections to the watch; only the equivalent of a switch opening or closing is present (high resistance or low resistance respectively). The whole circuit operates from 12 V DC, which can readily be supplied in the field from batteries. The stop-watch used is a desk-model equipped with sockets for external triggering (as well as ordinary start/stop and reset buttons) and is available from RS Components Ltd. It is powered by a single 1.5 V AA battery. Stop-watch timing, offering only 10 ms resolution, was inadequate for use with the 10 mm sensor. A digital counter-timer in the form of a six-digit panel meter was obtained for this purpose (Laurel Electronics, USA). This was configured to provide a timing resolution of 1 ms. Rather than being driven by the solid-state switch to simulate button presses, this timer was activated directly by the logic-level voltage pulses generated by the half-monostables. No contact debouncing is involved in the triggering of this timer, and it can, if required, time intervals of $<1 \mu\text{s}$.

The control circuitry is assembled on a printed board and housed in a small splash-proof plastic instrument case. Apart from an on/off switch, operator controls mounted on the instrument involve only a manual reset button, which puts the flip-flops back into the reset condition ready to detect a target, and a flashing LED driven by the inverted (\bar{Q}) output of the flip-flops that visually confirms that the system is ready to use. Once a target has been detected, this LED goes off to confirm that the stop-watch has been activated. Audible confirmation of the operation of the device is provided by a brief beep from the stop-watch as each optical sensor is activated by the floating target.

TESTING THE PERFORMANCE OF THE NEW DEVICE

Testing was carried out in a 1.8 m long and 0.6 m wide interrill flow flume (glued sand board) inclined at 1.2° , as described by Dunkerley *et al.* (2001), with some supplementary testing done in a 3 m metal channel. Water was recirculated at known flow rates by peristaltic pumps. In testing over several days, water temperatures varied between 18 and 22 °C. The flow depths present in the flume, generally 1–3 mm, were measured with a computer-controlled gantry and electronic needle gauge, as described by Dunkerley *et al.* (2001).

Targets were released onto the surface of the flowing water a short distance upstream of the optical sensors, using non-serrated forceps. These were preferred to serrated ones, since the targets must remain planar in order to float above any roughness elements that might protrude from the bed into the flow, and which could catch on bent edges of a torn target. Between repeated uses the targets were momentarily placed on a dry cloth in order to remove adhering water.

Several tests of performance were made. In the first, reflective targets were launched at the same time as injections of fluorescein dye (approximately 0.2 ml). The two tracers were then followed along the course of the flume in order to look for any possible lagging of the floating targets.

The second set of tests examined the effect of changing target diameter. The four target sizes were each released at a point 100 mm upstream of the sensor. The 10, 40 and 100 mm sensors were tested, and each measurement of flow speed was repeated ten times to derive a mean and a measure of variance.

The third set of tests examined the effect of changing the separation of the sensor and the upstream target release point. This was done to see whether there was a significant lag distance through which the targets accelerated from rest. Each size of target was released ten times from each of five distances upstream of the sensor: these were 0, 2.5, 5, 10 and 20 cm.

A set of analyses was made in order to compare speeds measured with the 10, 40 and 100 mm probes. The comparative tests were made under identical conditions in the test flume. These tests used 20 mm diameter targets released 100 mm upstream of the sensor.

In evaluating the effects of the different experimental methods on measured surface speeds, differences in outcomes were evaluated using small-sample *t*-tests (Freund, 1974). The criterion for significance was a probability of <0.05 for the measured differences being the product of chance.

RESULTS

Floating targets in comparison with liquid dye

In the tests where dye and a reflective target were simultaneously released, and the two tracers tracked through 0.5–1.0 m, each arrived downslope at the same instant. This experiment was repeated multiple times in order to confirm that there was no tendency for the floating target to lag the liquid dye. The absence of any such lag is consistent with the calculations presented above, which showed that the target masses being carried were, at most, a few percent of the maximum mass that could be carried by the surface tension film.

Mean surface speeds by optical tachometer and dye timing

In the test flume, eight different discharges were used to generate flows of different speeds. The surface speed of each was measured repeatedly, ten times with the 100 mm optical tachometer and five times with conventional dye-front arrival timing over a 50 cm flow path. The two sets of results (Table II) show a very good correspondence, with surface speeds ranging (by dye and tachometer respectively) from minima of 15.6 cm s⁻¹ and 16.6 cm s⁻¹ to maxima of 42.5 cm s⁻¹ and 43.8 cm s⁻¹. Though, in general, the two sets of results are accordant, the mean difference between them across the eight flow rates is 0.84 cm s⁻¹. Given the present uncertainty about the correct value of the coefficient α used to convert surface speeds to profile mean speeds, this difference

Table II. Comparison of speeds measured using conventional dye timing across a 50 cm flow path and the 100 mm optical tachometer

Imposed discharge (cm ³ s ⁻¹)	Optical tachometer			Dye timing		
	Mean surface speed (cm s ⁻¹)	Standard deviation (cm s ⁻¹)	No. of replicate measurements	Mean surface speed (cm s ⁻¹)	Standard deviation (cm s ⁻¹)	No. of replicate measurements
13.3	16.6	1.31	10	15.6	0.24	5
20.0	21.0	1.17	10	21.8	0.15	5
26.7	24.9	1.78	10	27.1	0.08	5
33.3	27.6	1.76	10	29.7	0.05	5
40.0	31.2	2.13	10	33.3	0.05	5
53.3	37.3	3.86	10	39.1	0.04	5
66.7	40.7	5.52	10	40.8	0.06	5
80.0	43.8	5.46	10	42.5	0.03	5

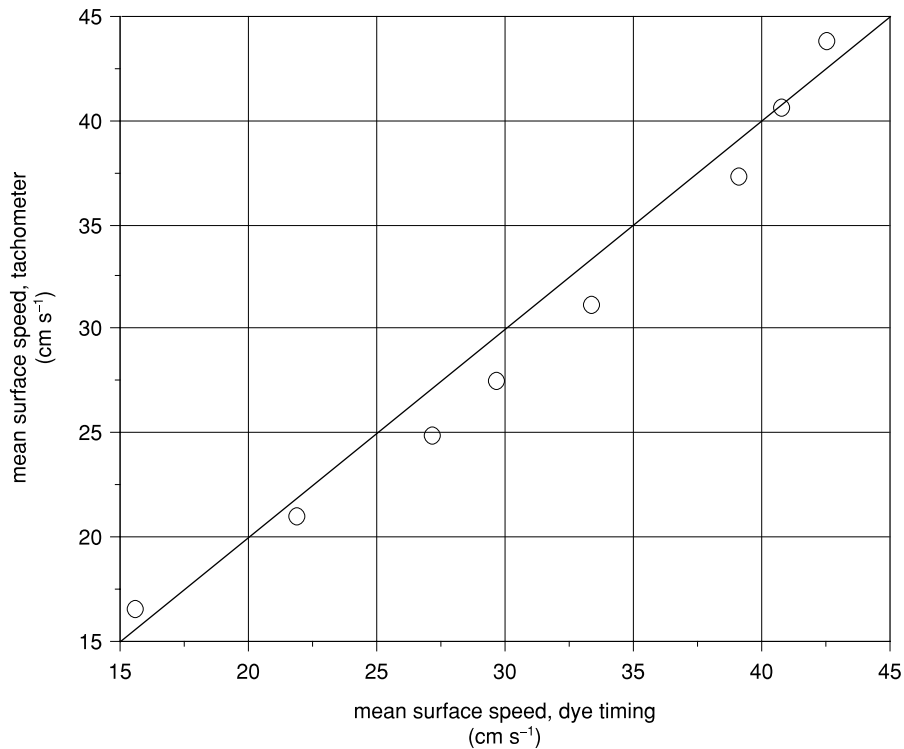


Figure 3. The relationship between mean surface flow speeds measured using the optical tachometer with 100 mm sensor, and dye timing across a 50 cm flow path. The line of perfect agreement is also shown. Each point represents the mean of ten tachometer measurements and five dye timings

is probably not important. Furthermore, it is at least as good as that achieved by Katz *et al.* (1995) using a more complex video timing system. A curvilinear relation between dye and tachometer speeds is evident in the data (Figure 3). Other spot measurements of speed and supplementary testing in the longer (3 m) channel referred to earlier (not detailed here) confirmed that this reflects acceleration (i.e. incomplete equilibration) of the flow along the course of the shorter (1.8 m) flume. Owing to the 50 cm path used for dye timing, which extended some distance upstream of the tachometer (this being placed at the mid-point of the dye path), the dye results are perturbed by the uppermost part of the dye path involving slower flow speeds than the downslope parts. When surface speed is plotted against the imposed discharge, the tachometer results are almost perfectly described by a second-order polynomial regression, whereas the dye timing data are less well fitted and indicate that the increase of surface speed with imposed discharge breaks down at the higher end of the range of flows when flow equilibration was least perfect.

A notable difference between the dye and tachometer data is the much lower variance of the dye data (Table II). The electronic timing in the tachometer avoids any perturbation by human reaction time or judgement, which must affect the dye timing. Thus, whilst some of the variance in tachometer results may reflect poor target emplacement, the bulk of the variability probably reflects real flow variability that is simply not resolved in the dye timing, since this integrates the flow through a sampling period from five times longer (for the 100 mm tachometer sensor) to 50 times longer (for the 10 mm sensor).

The effect of target diameter

Comparisons of differences among mean surface speeds derived using four different sizes of reflective target (Table III) using small-sample *t*-tests indicate that there is no significant difference among the 5, 10 and 25 mm targets. The 20 mm target gave mean travel times about 30 ms shorter, and hence flow speeds about 6% faster. In view of the statistically indistinguishable times for both larger and smaller targets, it is likely that this

Table III. Results of timing tests using reflective targets of four different diameters. Available results are presented for the 10, 40 and 100 mm sensors. All tests were carried out at the same imposed flow rate of $40 \text{ cm}^3 \text{ s}^{-1}$. The 5 mm target was not tested with the 10 mm sensor. Each mean and standard deviation were derived from ten replicate measurements. All targets were released 100 mm above the optical sensors

Target diameter (mm)	10 mm sensor		40 mm sensor		100 mm sensor	
	Mean surface speed (cm s^{-1})	Standard deviation (cm s^{-1})	Mean surface speed (cm s^{-1})	Standard deviation (cm s^{-1})	Mean surface speed (cm s^{-1})	Standard deviation (cm s^{-1})
5	–	–	19.7	1.42	20.8	0.92
10	20.9	0.83	21.8	3.13	20.5	0.84
20	20.8	0.67	22.5	2.72	22.0	0.93
25	20.7	0.76	20.9	1.74	20.7	1.45

Table IV. Results of timing tests in which 10 mm diameter reflective targets were released at varying distances upstream of the three sizes of optical sensor. All tests were carried out at the same imposed flow rate of $40 \text{ cm}^3 \text{ s}^{-1}$. Mean and standard deviation were derived from ten replicate measurements

Upstream release distance (mm)	10 mm sensor		40 mm sensor		100 mm sensor	
	Mean surface speed (cm s^{-1})	Standard deviation (cm s^{-1})	Mean surface speed (cm s^{-1})	Standard deviation (cm s^{-1})	Mean surface speed (cm s^{-1})	Standard deviation (cm s^{-1})
0	22.8	2.55	25.8	1.87	23.3	0.77
25	25.5	2.71	26.9	2.66	23.6	1.06
50	25.6	1.84	25.3	2.15	24.3	0.90
100	26.5	2.45	26.2	1.41	24.5	0.84
200	26.7	3.50	28.7	3.22	25.6	0.98

Table V. Regression models linking surface speeds measured using the 10, 40 and 100 mm tachometer sensors with the upstream release distance. All tests were made using a fixed imposed discharge of $40 \text{ cm}^3 \text{ s}^{-1}$, and using a 10 mm reflective target. Linear regression equations are of the form $\text{Surface speed (cm s}^{-1}\text{)} = a + b (\text{Release distance, mm})$. Statistically significant models are marked with an asterisk

Sensor length (mm)	a	b	r^2	Probability
10	25.4	0.007	0.83	0.0001*
40	25.4	0.014	0.59	0.0015*
100	23.5	0.010	0.95	0.0001*

difference is an artefact of the particular test, such as a temperature difference on the day when the 20 mm targets were tested. Even were it a genuine oddity of 20 mm diameter targets (which seems unlikely), a variation of 6% is probably negligible for practical purposes.

The effect of distance separating target release point and sensor

In 80% of paired comparisons by t -test, speeds estimated from targets released at the upstream sensor (i.e. with no distance allowed for target acceleration) were statistically indistinguishable from results where target release was 25, 50, 100 or 200 mm (Table IV). In the remaining 20% of cases, there was a difference in speeds. Linear regression analyses of mean surface speed from the ten replicate measurements made for each release distance against release distance show a statistically significant positive relation for all three sensors (Table V).

Thus, the targets do accelerate following release, though the speed increases are small. The speed measured from targets released directly adjacent to the sensor differed by no more than a few percent from those where up to 200 mm was allowed for acceleration. Clearly, therefore, in most cases the targets accelerate very rapidly. According to the linear regression models, the percentage increase in mean surface speed resulting from increasing the target release distance from 50 to 100 mm is 1.3%, 2.7% and 2.1% for the 10 mm, 40 mm and 100 mm sensors respectively. The conclusion drawn from these tests is that, in the bulk of cases, release distance is unimportant, and that any dependence will be small if an upstream release distance of at least 50 mm can be employed. Where release distance is zero, measured speeds may be 5% low in 20% of replicate measurements.

The effect of sensor separation (10, 40 or 100 mm)

Under flow conditions as similar as could be achieved across several days of testing at a fixed imposed discharge of $40 \text{ cm}^3 \text{ s}^{-1}$ (but somewhat varying water temperature), the 10 mm sensor (using millisecond timing) yielded a mean surface speed of 20.8 cm s^{-1} . The 40 mm and 100 mm sensors (using the lesser 10 ms timing resolution) yielded 21.2 cm s^{-1} and 21.0 cm s^{-1} respectively. There is no statistically significant difference among these mean speeds according to small-sample *t*-tests, and it can be concluded that the tachometer measurement of surface speeds across a flow path of as little as 10 mm yields results as reliable as those from the longer sensors.

DISCUSSION AND CONCLUSIONS

The above results confirm that the optical sensing of floating targets, combined with stop-watch or better timing, provides a simple, reliable and repeatable means of measuring surface flow speeds in shallow flows. Variations in target diameter, upstream target release distance, and optical sensor spacing across the wide test ranges reported earlier are generally only associated with changes of a few percent in measured surface speeds. In practical use, the tachometer would be used with a fixed target diameter and release distance, and probably also sensor size, for internal consistency and strict comparability of repeat measurements. The wide variations tested here were introduced primarily to explore the sensitivity of the tachometer to variations in test conditions. The results make it clear that the method exhibits only limited sensitivity to these variations in the test conditions. Given that measurements are acceptable even for zero upstream release distances, the use of a 10 mm tachometer sensor provides virtual 'spot' readings of surface speed.

The aluminium targets cost virtually nothing to produce, and are re-usable. Compared with the use of dyes, they offer the advantage that no chemicals are released into the environment. Additionally, measurements can be repeated immediately, there being no need to wait for residual dye clouds to clear from the water. The great advantage of the new device, however, is the ability to measure speeds along very short flow paths. This enables speed variation to be mapped in considerable detail, and eliminates the need to rely on averages obtained from the longer flow paths required for manual dye timing. Finally, the use of electronic sensing completely eliminates human judgement and reaction time as an influence degrading the precision of measurements of flow speed. However, the tachometer requires more care in target release than does the injection of a dye slug. The device has been tested under simulated rain without difficulty. The floating targets exhibit no greater effect from drop impacts than does a cloud of dye.

Despite the generally good performance of the tachometer, there are several limitations to its application.

The requirement that the reflective targets float freely on the water surface means that the tachometer is not suitable where the flow passes through grass turf, for example, or where bed grains protrude through the water surface creating gaps too narrow to allow the free passage of the target. In such cases, a liquid dye tracer would still have to be employed. Nevertheless, the device has been used successfully in runoff experiments on natural dryland surfaces in arid western New South Wales, Australia. These involved shallow flows over irregular soil surfaces.

There is a significant variance in some of the repeat tests. Whilst much of this probably reflects real speed fluctuations in the tachometer measurements that span some tens of milliseconds, and that are concealed in dye timing through one to several seconds, there may be other causes of minor performance irregularity. One such cause that may have had an influence on those few results where an unusually low speed was recorded is wet

forceps. If the target is linked to the forceps by a droplet of water that has to be drawn out and broken to overcome surface tension forces, then the release of the target is not as clean as when dry forceps are available and the target is released without drag. Another cause of poor-quality measurements needing care is inadvertent insertion of the target and/or forceps into the flow. Repeated experimentation showed that the optimum means of releasing a target is to hold it parallel to the water surface, and to drop it from a height of a few millimetres.

When the flow trajectory above a measurement point is strongly curved (such as flow bypassing a protruding obstacle), and a small (5 or 10 mm) target is used, it can be difficult to judge where to release the target in order to ensure that it passes directly beneath the optical sensors. This difficulty is most easily overcome by using a larger target, but checking the flow trajectory with a drop of dye before releasing a small target provides an alternate aid.

The AC-coupling used in the detector circuit results in a minimum speed that can be sensed. This minimum is quite low ($<2 \text{ cm s}^{-1}$), and could be reduced by straightforward circuit adjustments if very slow flows had to be observed.

The final factor affecting the usefulness of the new device is precisely the same as in the case of dye timing. This is uncertainty over the coefficient α that is employed to convert surface flow speeds to profile mean speeds. For smooth laminar flow, α is 0.65, and for turbulent flow it is 0.8 (Dunkerley, 2001). However, the correct value for use on surfaces carrying varying grain and form roughness is only poorly known. By providing higher-precision data on surface speeds, the device described here will facilitate attempts to refine further the relationship between surface and profile mean flow speeds for such conditions. In the meantime, the tachometer will be a useful tool in the exploration of non-uniform flows, with the key ability to measure flow speeds across a 10 mm flow path. This provides virtual spot readings of flow speed that have hitherto not been achievable in geomorphic investigations.

ACKNOWLEDGEMENTS

I thank David Tooth, workshop technician in the School of Geography and Environmental Science, for skilfully fabricating the mechanical components of the sensors for the optical tachometer.

REFERENCES

- Abrahams AD, Parsons AJ, Luk S-H. 1986. Field measurement of the velocity of overland flow using dye tracing. *Earth Surface Processes and Landforms* **11**: 653–657.
- Adamson AW, Gast AP. 1997. *Physical Chemistry of Surfaces*, 6th edn. Wiley: New York.
- Barros AP, Colello JD. 2001. Surface roughness for shallow overland flow on crushed stone surfaces. *Journal of Hydraulic Engineering* **127**: 38–52.
- Beuselinc L, Govers G, Steegen A, Quine TA. 1999. Sediment transport by overland flow over an area of net deposition. *Hydrological Processes* **13**: 2769–2782.
- Bryan RB, Brun SE. 1999. Laboratory experiments on sequential scour/deposition and their application to the development of banded vegetation. *Catena* **37**: 147–163.
- Dunkerley DL. 2001. Estimating the mean speed of laminar overland flow using dye injection—uncertainty on rough surfaces. *Earth Surface Processes and Landforms* **26**: 363–374.
- Dunkerley DL, Domelow P, Tooth D. 2001. Frictional retardation of laminar flow by plant litter and surface stones on dryland surfaces: a laboratory study. *Water Resources Research* **37**: 1417–1424.
- Dunne T, Dietrich WE. 1980. Experimental investigation of Horton overland flow on tropical hillslopes. *Zeitschrift für Geomorphologie, Supplementband* **35**: 60–80.
- Fox DM, Bryan RB. 1999. The relationship of soil loss by interrill erosion to slope gradient. *Catena* **38**: 211–222.
- Freund JE. 1974. *Modern Elementary Statistics*. Prentice-Hall: London.
- Gilley JE, Finkner SC. 1991. Hydraulic roughness coefficients as affected by random roughness. *Transactions of the American Society of Agricultural Engineers* **34**: 897–903.
- Gilley JE, Kottwitz ER, Wieman GA. 1992. Roughness coefficients for selected residue materials. *Journal of Irrigation and Drainage Engineering* **117**: 503–514.
- Govers G, Rauws G. 1986. Transporting capacity of overland flow on plane and on irregular beds. *Earth Surface Processes and Landforms* **11**: 515–524.
- Guy BT, Dickinson WT, Rudra RP, Wall GJ. 1990. Hydraulics of sediment-laden sheetflow and the influence of simulated rainfall. *Earth Surface Processes and Landforms* **15**: 101–118.
- Holland KT, Puleo JA, Kooney TN. 2001. Quantification of swash flows using video-based particle image velocimetry. *Coastal Engineering* **44**: 65–77.

- Katz DM, Watts FJ, Burroughs ER. 1995. Effects of surface roughness and rainfall impact on overland flow. *Journal of Hydrualic Engineering* **121**: 546–553.
- Li G, Abrahams AD, Atkinson JF. 1996. Correction factors in the determination of mean velocity of overland flow. *Earth Surface Processes and Landforms* **21**: 509–515.
- Nearing MA, Simanton JR, Norton LD, Bulygin SJ, Stone J. 1999. Soil erosion by surface water flow on a stony, semiarid hillslope. *Earth Surfaces Processes and Landforms* **24**: 677–686.
- Roels JM. 1984. Flow resistance in concentrated overland flow on rough slope surfaces. *Earth Surface Processes and Landforms* **9**: 541–551.
- Rouhipour H, Rosw CW, Yu B, Ghadiri H. 1999. Roughness coefficients and velocity estimation in well-inundated sheet and rilled overland flow without strongly eroding bed forms. *Earth Surfaces Processes and Landforms* **24**: 233–245.
- Welford AT (ed.). 1980. *Reaction Times*. Academic Press: London.