ISSN 2047-0371

Tracer investigations

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ABSTRACT: Tracers can be used to investigate the morphology and evolution of the drainage system that exists within and beneath glaciers. This paper explains how to use fluorescent dyes as tracers within studies of the glacier-hydrological system, detailing the type and quantity of dye required, the use and calibration of fluorometers used to detect the dye, and guidance on conducting tracer experiments. It then goes onto describe the parameters that can be calculated from collected dye breakthrough curves and their interpretation in terms of the likely morphology of the drainage system.

KEYWORDS: glacier-hydrology, dye tracing, fluorometers, rhodamine

Introduction

Investigating the structure and evolution of the drainage system within and beneath glaciers is a challenge because of its inaccessibility. Although some workers (Gulley 2009; Benn et al., 2009; Gulley et al., 2012) have been able to enter englacial and subglacial channels directly, elucidating the form of the glacier-hydrological system is usually performed by injecting fluorescent dyes into moulins or crevasses on the surface of the glacier and detecting the resulting dye return curve at a monitoring site on the proglacial stream. In this paper the methods used to conduct and analyse dye return curves are explained.

At first, understanding the structure of the glacier hydrological system was achieved by tracing injections of sodium chloride (Stenborg, 1969). More recently, fluorescent dyes have become the tracer of choice for glacier hydrology studies due to their greater detectability and the smaller quantities required. If a quantity of dye is injected into a moulin or crevasse, and then detected downstream (to give the dye breakthrough or return curve), the time of travel of the dye within the system, the spread of the dye breakthrough curve and the percentage of dye detected can be calculated. These trace characteristics can then be used to determine the morphology of the glacier-hydrological drainage system at the time of the test. In this paper the morphology of the system refers to the 'size, shape and roughness' of the drainage system (Willis et al., 2012) (characteristics which determine the efficiency of the system) and the structure of the hydrological system is defined as the 'location, alignment and interconnection' of the drainage routes (Willis et al., 2012).

Dye tracing can therefore be used to determine the drainage structure in terms of identifying the moulins which drain to a particular stream, and can determine changes in the drainage morphology between different parts of a glacier (e.g. the eastern and western sides of Midtdalsbreen, Norway, Willis et al. (1990, 2012)). It can also be used to identify changes in the morphology of the drainage system over the season and how this relates to the position of the snowline (Nienow et al., 1998); and changes in the relationship between the water velocity and discharge within a day, termed velocity-discharge hysteresis (Nienow et al., 1996; Schuler and Fisher, 2009). These studies on alpine glaciers have led to larger-scale studies of the drainage system beneath an outlet glacier of the Greenland ice sheet using both rhodamine dye (Cowton et al., 2013) and sulphur hexafluoride, a gas suitable for tracing over long distances (Chandler et al., 2013).

Instruments and dye

Types of dye

Fluorescence occurs when a substance absorbs electromagnetic radiation at the precise frequency needed to excite its electrons to a higher energy. As the electrons return to their lower energy state, this energy is emitted as light which typically has a longer wavelength than that absorbed. Fluorescent dyes used for tracing transform a high proportion of the absorbed energy to emitted energy, and can be detectable at very low concentrations (e.g. to a minimum of 0.01 ppb rhodamine with a Turner Designs fluorometer (Turner Designs, 2010)). Dyes used for tracing include fluorescein, tinopal CBS-X, rhodamine B powder and rhodamine WT liquid. The rhodamine dyes are most commonly used, but fluorescein or tinopal can be used alongside them if traces are to be conducted simultaneously, since they emit light at different wavelengths to those of the rhodamine dyes (Nienow et al, 1998; Fountain, 1993). Care should be taken not to ingest dye and gloves should be worn to avoid skin contact. Consult the manufacturer's data sheet for details of safety considerations, and follow local guidelines if dye is to be injected into drinking water supplies or environmentally sensitive areas.

Quantities to use

The quantity of dye required to produce a detectable dye breakthrough curve depends on the discharge of the stream at the monitoring site, the distance to be traced, and importantly the morphology of the drainage system beneath the glacier. The quantity of dye required to trace a distributed system can be an order of magnitude larger than that needed to trace a channelized system. Caution is therefore recommended in the quantity of dye used initially, to prevent the dye being visible at the monitoring site. To estimate the quantity of dye required for tracing in open water streams Equation 1 can be used:

$$V_i = 3.14 \times 10^{-4} \left(\frac{0.305 Q_{max} d}{0.045 u}\right)^{0.94} C_p, \qquad (1)$$

where V_i is the volume of 21% rhodamine WT (l), Q_{max} is the maximum stream discharge at the downstream site ($m^3\ s^{-1}$), d is the distance to the downstream site (km), u is the mean stream velocity ($m\ s^{-1}$) and C_p is the peak concentration at the downstream sampling

Table 1: Quantities of dye used by selected investigators. RB is 100% rhodamine B powder, RWT is 21% rhodamine WT liquid, F is fluorescein and T is tinopal CBS-X. Quantities of rhodamine B in grams can be converted to an equivalent of rhodamine WT in ml by multiplying by 4.76. The minimum to maximum quantities used are stated. Proglacial discharge is generally an average between the time of injection and trace peak.

Investigator	Glacier	Distance traced (m)	Proglacial discharge ($m^3\ s^{-1}$)	Type of dye	Quantity of dye (g for RB and F, ml for RWT and T)	Time of year
Willis et al., 1990	Midtdalsbreen, Norway	1100-1650	0.2-3.3	RB	140-300	June to August
Willis et al., 2009	Brewster Glacier, New Zealand	~500 -1500	-	RWT	50-70	January to March
Nienow, 1993 (1990 data)	Haut Glacier d'Arolla, Switzerland	1028-1426	0.5-4.1	RB	30-75	June
		1028-1271	0.6-3.3	F	100-200	June
		999-3300	2.0-6.3	RB	10-400	July
		670-2378	2.1-6.4	F	100-250	July
Fyffe, 2012	Miage Glacier, Italian Alps	997-5867	1.7-10.7	RWT	40-280	June to September
Cowton et al., 2013	Leverett Glacier, Greenland Ice Sheet	1250	<1-300	RWT/RB	300-2000/ 250-1000	April to August
		3600	15-400	RWT/RB	4000-5000/ 750-3000	May to August
		6600	15-400	RWT/RB	9000-10000/ 1500-5000	May to August
Hasnain et al., 2001	Dokriani Glacier, India	930-2300	9-30	RWT	40-50	July to September
Fountain, 1993	South Cascade Glacier, Washington State, USA	485-3335	0.2-0.8	RWT	70-1000	July to September
		485-1355	0.2-0.8	T	1000-3700	July to September
Seaberg et al., 1988	Storglaciären, Sweden	~900-1000	0.1-0.7	RWT	102-208	June to August

site (ppb) (adjusted to SI units from Kilpatrick and Wilson (1989)). The quantity of dye used by other investigators can also be used as a guide, see Table 1.

Measuring fluorescence

A fluorometer is used to detect the dye return curve when it reaches the proglacial stream. Fluorometers supply a beam of radiation at the excitation wavelength, and measure the intensity of light emitted by the fluorescent dye, which is proportional to the concentration of dye in solution.

Two common brands of modern fluorometer are the Seapoint rhodamine fluorometer and Turner Cyclops-7 fluorometer, both of which can be set up to log to a Campbell Scientific data logger or similar. Values should ideally be recorded every 1 to 10 seconds, with data outputted as an average for each minute, especially if sharply peaked return curves are expected, although a lower logging interval is suitable for broader return curves or after the peak has passed through. Measurements should begin well before the trace comes through (preferably before the dye is injected) and continue until well after the fluorescence has returned to background levels. This can be over a day if a less efficient drainage system is traced, or only a few hours if the system is efficient and the trace is conducted close to the proglacial stream outlet.

To position the fluorometer in the stream it can be attached to a length of angle iron (e.g. dexion), which is then secured to the bank and/or river bed (e.g. using expansion bolts, rope or boulders). The fluorometer should be positioned low enough in the water to reduce the influence of sunlight on readings, although using the fluorometer's shade cap also reduces this effect. Note that the fluorescence of dyes can be influenced by the stream pH (the fluorescence of rhodamine WT is stable within a pH range of 5.5 to 11 (Keystone Aniline Corporation, 2002)).

Calibrating a fluorometer

Fluorometers give relative values of fluorescence intensity, which is logged as a value in volts. To convert this to dye concentration the fluorometer must be calibrated, preferably for each dye lot (as there may be slight differences between batches). The calibration procedure allows the definition of the relationship between the dye concentration and the voltage measured by the fluorometer. The value in volts should vary linearly with dye concentration, apart from at very high or low concentrations. It is important to calibrate the fluorometer in the field to ensure the water temperature is similar to that during a trace, because water temperature is the most significant factor that varies the relationship between fluorescence and dye concentration (Wilson et al., 1986). Furthermore, chlorinated tap water should not be used for calibration as chlorine affects the fluorescence of rhodamine dyes (Wilson et al., 1986). Suspended sediment in the proglacial stream can fluoresce within the same wavelength band as the dye. This means the measured background fluorescence is positive and can be variable (Hubbard and Glasser, 2005), although this is most pronounced using fluorescein (Nienow et al., 1998). The value in volts used in the calibration must therefore be corrected to remove the influence of the background fluorescence.

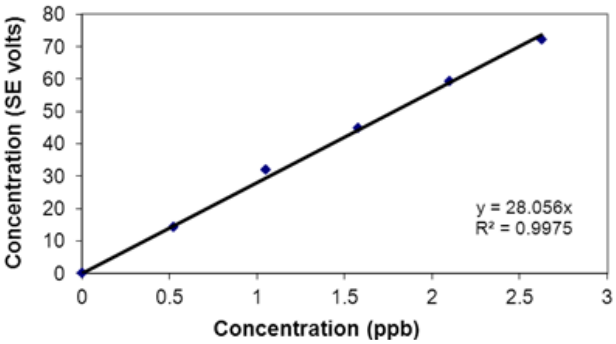

Figure 1: Calibration curve giving the relationship between the voltage measured by the fluorometer and the dye concentration.

Fluorometer calibration involves recording the voltage measured by the fluorometer while it is in solutions with a known dye concentration. Around 10 standards of different dye concentrations should be measured, spanning the measureable range of the fluorometer, and with an emphasis on lower concentrations in case of non-linearity in the calibration relationship. An example calibration procedure for 21% rhodamine WT is as follows:

1. Have ready two completely clean buckets pre-marked with a 5 litre

level, dye, a µl pipette, and have the fluorometer logging

2. Fill both buckets with 5 litres of stream water, and add the fluorometer to the second bucket
3. To define the background voltage, record several logged values of the fluorometer voltage (with logged values ideally averages of several readings)
4. Add 250 µl of dye to the first bucket, and mix it thoroughly
5. Replace the pipette tip, and then take 250 µl from the first bucket and add this to the second bucket, mixing thoroughly (this gives a concentration in the second bucket of 0.525 ppb rhodamine WT)
6. Take several readings of the voltage within the second bucket
7. Replace the pipette tip or wash it out in stream water repeatedly
8. Add a further 250 µl of the first bucket solution into the second bucket, and mix thoroughly (to give a concentration of 1.05 ppb rhodamine WT)
9. Repeat steps 6. to 8. until the desired maximum voltage has been reached.

The average background voltage should then be removed from the voltage measurements, with these values plotted against the dye concentration in the second bucket, to give a relationship between voltage and dye concentration (Figure 1). Then, once the background voltage specific to the dye breakthrough curve has been determined (usually by averaging values measured prior to the trace injection), and then subtracted from the logged return curve, the dye concentration of the return curve can be calculated. The background voltage may not be constant (as shown in Figure 3) but can vary over time, necessitating the use of a varying background correction.

Conducting dye trace experiments

Dye should be injected into a supraglacial stream that flows directly into a freely draining crevasse or moulin (Figure 2). Care must be taken to use channels which are ice walled and free of snow (snow should be removed if it is covering a moulin), and dye should not be injected into standing water. The bottle containing the dye should be well flushed with stream water so that all of the dye enters the stream. When working on a snow-covered glacier (especially in regions of crevasses or moulins), all field members should be roped-up and know what to do in the event of a fall. Consult a qualified professional if unsure.

If the purpose of the study is to determine the seasonal evolution of the glacier-hydrological system, it is advised to conduct dye traces into moulins at a variety of distances from the proglacial stream outlet. Moulins at increasingly higher elevations will become traceable as the season progresses and the snowcover melts. Traces into the selected moulins can be repeated over the season to identify the changes in the resulting return curves. In these cases traces should be made at a similar time each day (e.g. between 11:00 and 15:00, (Willis et al., 2009)), to reduce the influence of diurnal hydrological fluctuations. Conversely, if velocity-discharge hysteresis is the object of the study then traces should be injected into the same moulin at intervals throughout one day (Nienow et al., 1996).

Figure 2: Injecting rhodamine WT liquid dye into a moulin on Miage Glacier, Italian Alps.

Dye trace parameters

Once the dye breakthrough curve values have been converted into dye concentration several parameters can be calculated that describe the shape of the curve and the speed of the dye trace as it travels through the glacier. It is not correct to assume that the values derived will be applicable along the entire length of the drainage network – the channel morphology and water velocity may vary spatially. Note that for broad traces, especially with multiple peaks, the derivation of the parameters described below can be difficult to determine and not accurate (e.g. the difficulty in defining the start and end of a broad return curve such as that shown in Figure 5).

Nevertheless, to analyse a breakthrough curve first find the time to peak (t_m), and time to half the peak on the rising (t_1) and falling (t_2) limb of the breakthrough curve (s). From the time to peak the average trace velocity can be calculated using Equation 2:

$$u = \frac{d}{t_m}, \quad (2)$$

where u is the trace velocity (m s^{-1}) and d is the straight line distance to the injection site (m) (Seaberg et al., 1988, p 222). The value calculated in Equation 2 gives the minimum velocity of the water because the actual distance travelled by the water will be greater than measured due to stream sinuosity.

The dispersion coefficient (D) of the breakthrough curve can be determined (as this is "a measure of the rate at which the dye-concentration peak broadens relative to the rate at which it is transferred through the glacier" (Willis et al., 1990, p93)) using:

$$D = \frac{d^2(t_m - t_i)^2}{4t_m^2 t_i \ln\left[2\left(\frac{t_m}{t_i}\right)^{\frac{1}{2}}\right]}, \quad (3)$$

(Seaberg et al., 1988, p222) where t_i equals the time at which the dye concentration is half of the peak, either on the rising or falling limb of the dye return curve. The equation is solved iteratively for t_m, allowing D to be found. To do this complete Equation 3 for t_i on the rising limb and subtract Equation 3 completed with t_i on the falling limb, then vary t_m in both variations of the equation until the difference between the equations approaches zero. At this point take the value of t_m and use it to calculate D for both values of t_i. As the dispersion of the tracer is proportional to its velocity (u), the constant of this proportionality (or the dispersivity (b)) can be calculated (Equation 4).

$$D = bu, \quad (4)$$

(Seaberg et al., 1988, p224). If the drainage system has interlinking passages then the dispersivity is a measure of the length of the passages, so a large dispersivity points to a more distributed network.

The apparent mean cross sectional area (A_{sm}, m^2) of the channel network can also be calculated (Equation 5). If repeat traces are conducted into the same moulin then this can be used to identify changes in the drainage system morphology from a broad, low, distributed system with a large cross-sectional area to a discrete channelized system.

$$A_{sm} = \frac{Q}{u}, \quad (5)$$

where Q is the mean discharge between the injection and detection point, calculated as the average of the supraglacial and proglacial stream discharge over the time of the test (from injection until the end of the trace return curve) (Nienow et al., 1998, p 828). Using the mean discharge decreases the possibility of overestimating the cross sectional area.

To find the volume of dye recovered (V_r, ml) the equation used to calculate the discharge of a stream from the slug-injection method (Kilpatrick and Cobb, 1985, p6) can be rearranged (Equation 6):

$$V_r = \frac{S^{-1}\left(\frac{1}{1.649\times10^{-8}}\left(Q_p A_c\right)\right)}{C_i}, \quad (6)$$

where S is the specific gravity of the dye used (1.15 for rhodamine WT), Q_p is the average proglacial discharge during the time taken for the dye return curve to pass through (m^3 s^{-1}), A_c is the area under the dye curve in ppb minute^{-1}, and C_i is the concentration of the dye prior to injection (ppb). A_c can be calculated by summing the positive dye concentrations composing the return curve (once the background has been removed) and multiplying by the logging interval in minutes. Sorption of rhodamine B onto

sediment can reduce the quantity recovered (Hubbard and Glasser, 2005), although rhodamine WT is more resistant to adsorption (Smart and Laidlaw, 1977).

The relationship between discharge and velocity can be used to infer whether the channel is full and pressurised (closed channel conditions) or only partially full and at atmospheric pressure (open channel conditions). These relationships are only valid over short periods (within a diurnal cycle) since changes to the cross-sectional area through melting of the channel sides or ice deformation are less likely to be significant. The relationship is found by fitting a power function (Equation 7) to several measurements of channel velocity at different discharges:

$$u = kQ^m \quad (7)$$

(Nienow et al., 1996, p 1413), where *m* relates to the conditions in the channel and *k* is a constant. When the channel is full, discharge can only increase via an increase in velocity (assuming no change in channel dimensions), so velocity and discharge are directly related and m = 1. Under open channel conditions, the channel cross-sectional area can increase as well as the velocity, so that m < 1. However the application of power functions to determine channel conditions can be erroneous because the tributary moulin and main channel discharge can vary out of phase, or water can be forced to back up in the moulin or tributary channel, decreasing the trace velocity (Nienow et al., 1996).

Interpreting traces

To determine the morphology of the drainage system from dye return curves it is necessary to know the likely trace parameters associated with different channel types. Generally, traces conducted into a system which is efficient and composed of discrete channels will consist of a singular peak. The trace will have a fast velocity (typically 0.3-0.5 ms^{-1} in small Alpine glaciers (Nienow et al., 1998)), a low dispersion coefficient and dispersivity (typically less than 10 m (Nienow et al., 1998)), and a high percentage dye recovery (Figure 3).

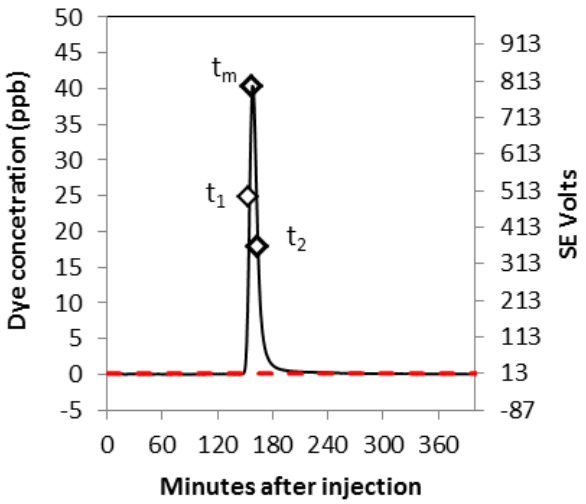

Figure 3: An example of a breakthrough curve indicative of a channelized drainage system, with t_1, t_m and t_2 shown as diamonds (t_1 and t_2 do not have a concentration that is exactly half of t_m because of the rapid change in dye concentration). The raw SE volts value from the fluorometer is given on the secondary axis, with the dashed red line the background that was removed before the calibration was applied to give the dye concentration.

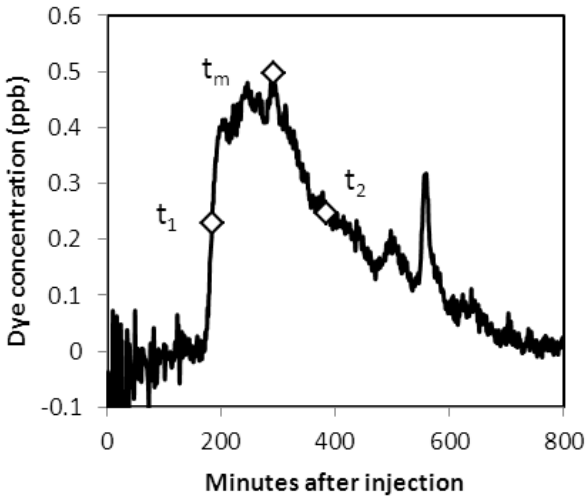

Figure 4: An example of a breakthrough curve with a shoulder on the falling limb, with diamonds showing the position of t_1, t_m and t_2.

The slower the trace and the greater the dispersion coefficient and dispersivity, the less efficient the drainage system. However, this may not necessarily imply that the drainage system is distributed, but may indicate that water has become trapped in part of the system (likely during high flows if the input discharge increases at a rate greater than the channel can expand by melting of the channel sides); or that the

conduit roughness is relatively large due to small input discharges (Gulley et al., 2012). Return curves with a pronounced shoulder on the falling limb may indicate storage of water in part of the system (Figure 4).

Traces with a very slow velocity (typically around 0.025 ms^{-1} (Nienow *et al.,* 1998)), especially with multiple peaks, are indicative of a distributed drainage system, usually thought of in terms of a linked cavity network (Figure 5). This type of system is inefficient and gives broad breakthrough curves with low percentage dye returns (signifying that either water has become stored subglacially or that the dye has been returned at too low a concentration to be detected).

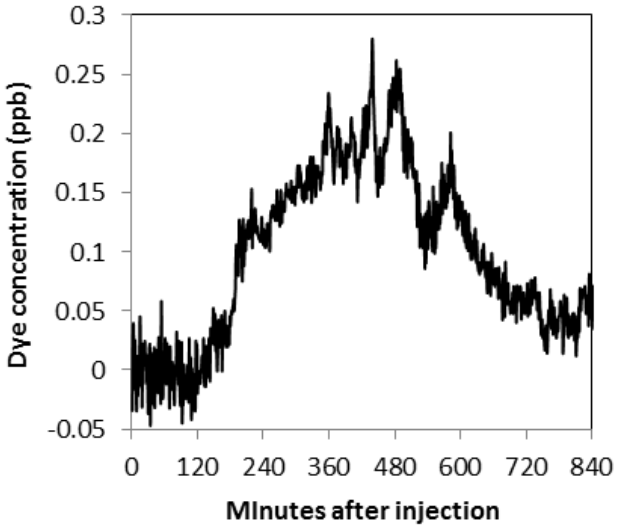

Figure 5: An example of a multi-peaked breakthrough curve indicative of a distributed system. This curve could be seen as just variation in the background fluorescence but subsequent traces into the same moulin confirmed this was a breakthrough curve.

Conclusions

Fluorescent dyes can give an insight into the morphology and seasonal evolution of a glacier's hydrological system. Rhodamine dyes tend to be preferred and the quantity required for a clear breakthrough curve is determined by the morphology of the drainage system, the distance traced and the proglacial discharge. Modern fluorometers can be installed at the proglacial stream outlet and used to detect the dye breakthrough curve at a high temporal resolution. The resulting return curve can be described using several parameters, which along with the return curve shape, can be used to identify the likely efficiency and morphology of the drainage system.

Acknowledgements

The author would like to thank the School of the Environment, University of Dundee for her studentship. Thanks to Joe Holden and Ben Brock for the loan of fluorometers, and to Pete Nienow and Tom Cowton for information on dye quantities. Helpful comments from David Chandler and Ian Willis greatly improved the manuscript.

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