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Sonde for Downhole Measurement of Water Turbidity and Dye Tracer Concentration

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ABSTRACT: A new flow-through field fluorometer sonde has been designed for use in downhole tracer tests in 2" boreholes. The instrument is capable of determining the partial concentration of two dye tracers present simultaneously in the water. In addition, turbidity can be measured if the water is free of tracers. Although the sonde is aimed at borehole hydrological investigations, it can also be used in surface waters.

1 INTRODUCTION

1.1 *The flow-through field fluorometer*

A flow-through fluorometer is an instrument for measuring the concentration of a dye tracer contained in the water flowing through it. A ray of monochromatic light excites the fluorescence of the dye. A detector yields an electric voltage of amplitude proportional to the fluorescence, and therefore, to the tracer concentration. Carefully chosen filters prevent excitation light from entering into the fluorescent light detector. The flow-through fluorometer has several advantages over the mechanical sampler commonly used in tracer tests:

- enhanced temporal resolution
- reduced manpower requirements
- no overhead costs such as lab analyses
- immediate result availability
- no contamination, no sample ageing
- no sensitivity to frost.

1.2 *Adaptation to boreholes*

Two years ago, we shrank the size of our first flow-through field fluorometer and designed a downhole sonde which could be used in 3" boreholes (Schnegg & Kennedy 1998). Only topologic changes were made, particularly those required by the higher pressure range.

1.3 *Necessity to lower the sonde diameter*

It quickly became apparent that the diameter of the downhole sonde was not adapted to the vast majority of existing wells. A subsequent effort in size reduction led to the design of a 2" sonde. This operation required the development of more complicated optics. Chapter 3 illustrates the use of the fluorometer in various applications. The appendix lists the characteristics of the 2" downhole fluorometer.

2 DESCRIPTION OF THE 2" DOWNHOLE FLOW-THROUGH FLUOROMETER

2.1 *The sonde*

The sonde is a stainless steel cylinder of 50 mm diameter (Fig. 1).

Figure 1. Two-inch diameter stainless steel fluorometer sonde with optional quick-connect fittings.

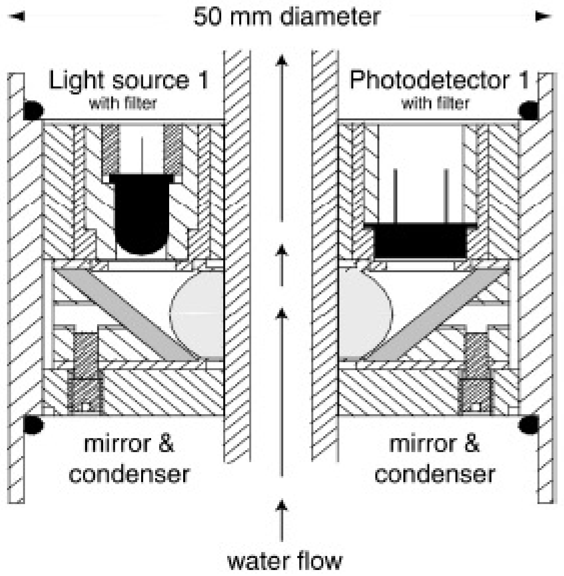

Figure 2. Optical cell of fluorometer sonde showing water flowing through a Pyrex glass tube. The light source is on the left and the fluorescence detector on the right. These two parts are seen in the same plane, but they are set up at right angles. Measurement occurs between the two condenser lenses. The second lamp/detector pair is not shown here.

No corrosion effects have been observed after several days of contact with salted water. Its optical cell (Fig. 2) consists of a 5 mm i.d. Pyrex glass tube standing on the symmetry axis of the cylinder. Both tube ends are linked to the liquid medium through perpendicular holes drilled in the metal casing. This design prevents daylight from entering. Waterproofness is insured by "O"rings. The inlet/outlets have threads permitting installation of quick connectors for plastic tubing leading to an external pump. However, pumps are not required if a natural stream is not completely absent. Material and configuration used in this design confers very long lifetime to the optical cell and eases cleaning operations.

All active optical parts are set up along two axes perpendicular to each others and to the tube. A LED (light emitting diode) is set on one axis, whereas a photodetector (photodiode) is mounted on another axis at 90 degrees. Carefully selected excitation and detection filters are inserted in front of the condensing lenses. To shorten the length of each axes, a mirror is set at 45 degrees in each light path. This additional device was required in order to achieve a sonde diameter of 2".

This setup is repeated on the two other branches of the axes with different sets of lamps and filters. With this double excitation – double detection scheme, the sonde is capable of simultaneously detecting two dye tracers with different spectral characteristics, such as:

- uranine (or pyranine) and rhodamine (sulfo-B, amido-G, WT).
- uranine and Tinopal (UV absorbing dye).
- Tinopal and rhodamine.

During a measuring cycle, the two lamps are ignited in turn. The response of both light sources (L1, L2) on both photocells (C1, C2) is measured. Signals L1C1 and L2C2 result from the fluorescent emission of both tracers eventually present in the water. A system of two equations of two unknown concentrations can be solved in real time on a monitoring PC, allowing for separation of two tracer concentrations (Schnegg & Doerfliger 1997).

If there is no tracer in the water, turbidity can be deduced from signal L2C1. Clean water produces only a small L2C1 signal due to residual Raman scattering. But the signal increases non-linearly with the turbidity of water. As for the tracer concentration, precise calibration of the sonde is necessary to convert the electrical response into turbidity units.

The upper part of the sonde hosts the signal preamplifiers which connect to the main cable.

2.2 *The cable*

The inexpensive signal cable provides both mechanical and electrical functions. It holds the sonde in the borehole, brings the power supply to the lamps and carries the two analog signals from the preamplifiers to the amplifiers and the AD converter of the data logger. Its length is virtually not limited since calibration can account for it (actually tested length : 400 m).

2.3 *The data logger*

The data logger is contained in a water-resistant plastic box, along with the battery. The sampling timing is generated by a microcontroller, the analog data is converted to digital and recorded on a memory card which can be downloaded to a PC at the end of the test.

3 FIELD EXAMPLES

The following field examples illustrate different general characteristics of the flow-through sonde. Parags. 3.1 and 3.2 apply to generic flow-through fluorometers, whereas parags. 3.3 and 3.4 are specific to a downhole sonde only.

3.1 *Enhancement of time resolution*

Comparisons of a tracer breakthrough curve (uranine) obtained with both a mechanical sampler (sampling interval : 40 mn) and a flow-through fluorometer (s. i. : 4 mn) have been carried out. Obviously, this instrument has a much better time resolution, providing detailed information on fast variations. Fig. 3 is an example of breakthrough containing a very well resolved, narrow (35 mn) peak of tracer that would probably have been missed by a sampler.

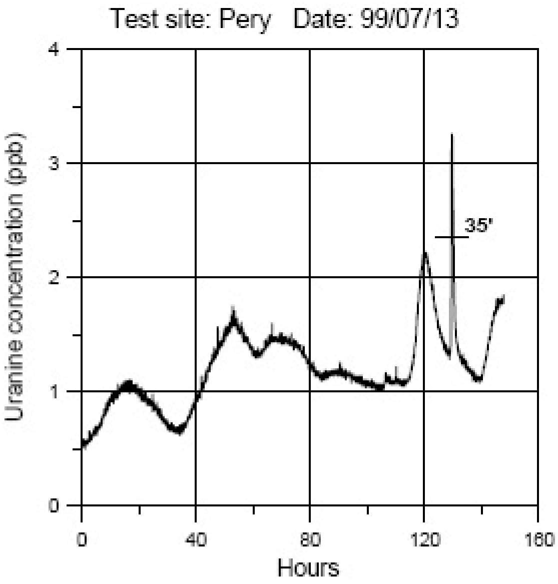

Figure 3. Example of a breakthrough curve showing the ability of the fluorometer to resolve narrow peak arrivals, even during tracer tests running over several days (sampling time: 4 minutes).

3.2 *Stream flow measurement*

To test the ability of the sonde to measure discharges accurately, two sondes have been installed on each bank of a stream at a distance of 400 metres from each other.

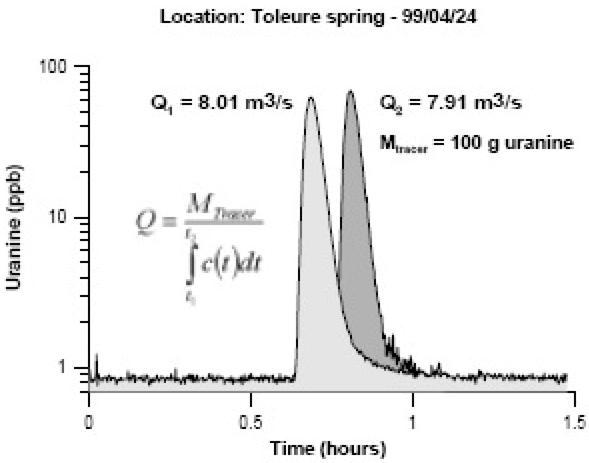

Figure 4. Use of 2 fluorometers to measure the discharge of a stream simultaneously. Note the good agreement of the results.

A mass of 100 g uranine yielded a peak on each instrument, from which discharges of 8.01 and 7.91 m^3s^{-1} were computed. It can be seen from Fig. 4 that a fraction of the uranine used would have produced peaks with a good s/n ratio, large enough to keep the achieved level of accuracy.

3.3 *Dilution experiments*

A downhole sonde monitors the flushing of tracer concentration in a well in which the water column was previously brought to a homogeneous concentration of uranine (Fig. 5). This experiment can be repeated at different depths to determine the medium conductivity as a function of depth. The relatively large cross-section of the optical cell favours rapid liquid displacements and fast response to concentration changes.

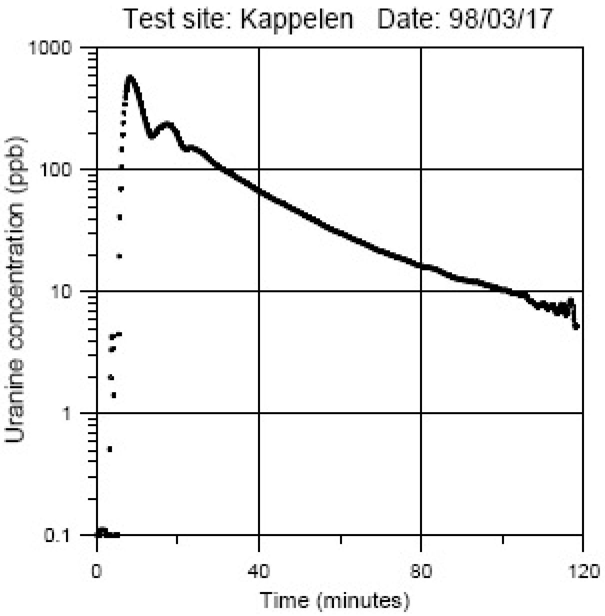

Figure 5. Dilution experiment performed in a 15-meter deep borehole drilled in the Swiss Molasse basin.

3.4 *Turbidity measurements*

Particles contained in water scatter the light beam of the fluorometer. By measuring the light intensity scattered at right angles, it is possible to deduce the turbidity value. Turbidity, as a function of depth, was measured in a 383-m deep artesian well with an important outflow (>1000 l/min), drilled in a confined karstic aquifer (Jurassic limestone) for supplying water to a neighbouring village. Other parameters such as electrical conductivity and temperature were known from previous logs. Stepwise variations of the three parameters clearly indicate the entry of productive water at different depths (Fig. 6). The water quality is uneven, however, and the turbidity measurement can be used as a criterion to select which segments of the borehole should be clogged up.

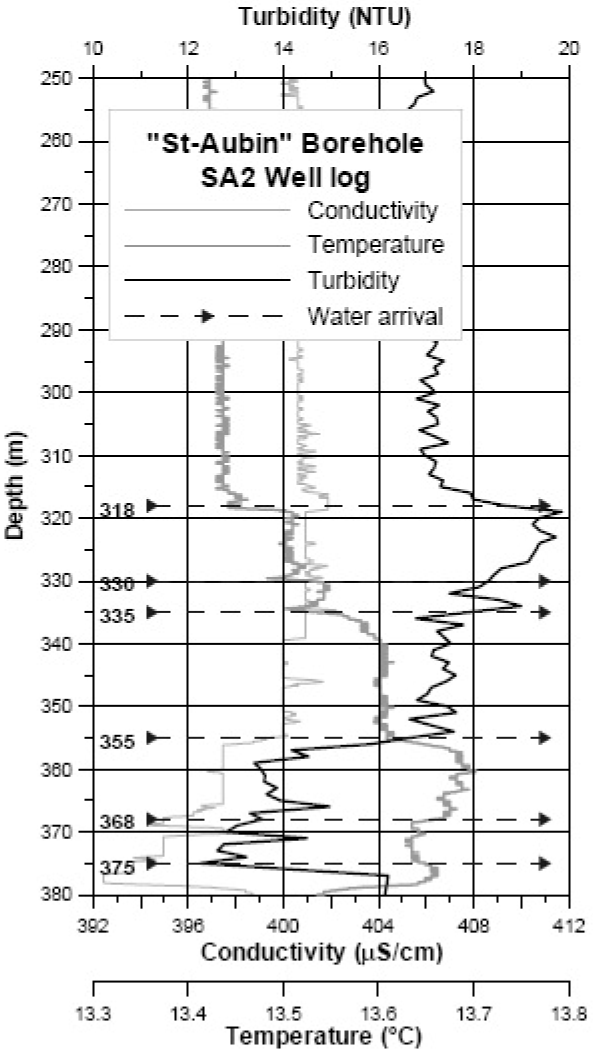

Figure 6. Well logs of the electrical conductivity, temperature and turbidity (not calibrated) of water in the St Aubin SA2 borehole. The lateral arrival of water from various aquifers produces noticeable parameter variations.

4 CONCLUSIONS

The downhole flow-through fluorometer can be successfully used in boreholes from 2" diameter, to measure the groundwater flow regime. Optics miniaturization makes the fluorometer suitable for detailed local measurements at any depth. The sonde design is based on a surface fluorometer with emphasis on size reduction. All properties of the surface instrument are retained. However, the shape of the downhole sonde is less convenient than the surface instrument for measuring small, discrete water samples in the laboratory. The 2" fluorometer sonde represents a major improvement over mechanical samplers in many respects, among which reduced manpower requirements and absence of overhead costs for subsequent laboratory analyses. The small size allows its use in most existing wells, yet without significant performance degradation with regard to the larger surface fluorometer.

5 APPENDIX : CHARACTERISTICS

Sonde:

Detectable tracers	: uranine + 1 optional tracer (1)	
Detection level (free of turbidity) and nominal gain for		
• uranine	: 0.02 µg/l	5 mV/ppb
• rhodamin B, G, WT	: 0.2 µg/l	0.5 mV/ppb
• Tinopal	: 0.2 µg/l	0.5 mV/ppb
Electrical noise	: 0.1 mV	
Turbidity measurement	: < 200 NTU	
Tested immersion depth		
• standard	: 70 m	
• with epoxy coating	: 400 m	
Max. cable length	: 400 m	
Sonde material	: stainless steel	
Sonde size		
• length	: 186 mm	
• diameter	: 48 mm	
• weight	: 1 kg 750	

(1) optional tracers: rhodamine B, G, WT, Tinopal

Data logger:

A/D converter	: 16 bit
Saturation level	: 2500 mV
Digital input/output	: RS232
Measuring interval	: 10 sec / 4 minutes / external
Shortest sampling time (ext.)	: 1 lamp: 3 sec 2 lamps: 7 sec
Recording medium	: PCMCIA SRAM memory card
Memory capacity	: 20-170 ksamples (6 channels)
Recording time	: 14-28 days (1 or 2 batteries)
Power supply	: 12 V
Battery capacity (1-2)	: 7- 14 Ah
Stand-by consumption	: 5 mA with lamps off

6 REFERENCES

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