A new borehole fluorometer for double tracer tests

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This abstract describes the principle and characteristics of a field fluorometer that was designed by our institute to provide automatic monitoring of tracer concentrations. Its shape and size allows its use downhole in boreholes with diameters of 3-inches and more to depths up to 50 meters. A double-excitation, double-detection optical scheme permits simultaneous concentration measurements of two different dye tracers and water turbidity. Although the optical filter set is selected for the dye tracer pair uranine (fluorescein) - sulforhodamine, other dyes can be used. Because of a favourable separation of their characteristics in the visible spectrum, these two tracers can be used simultaneously at two different injection sites. The instrument can measure the response of both dyes even when there is an overlap of the two tracing curves. Real-time measurement of the turbidity in the range of 0.02 to 400 nephelometric units is also of great interest.

A flow-through field fluorometer can be used in water of various origins and chemistry to measure very small dye concentrations. Although such an instrument is commercially available, it is generally of prohibitive cost to academic grants. Moreover, we were unable to find on the market a device of sufficiently small diameter so that it could be introduced in a well. We started down this path by first designing an automatic, inexpensive device, with the idea of replacing mechanical sampling systems because of their inherent disadvantages (Schnegg and Doerfliger, 1997). However, the 16 cm diameter of this device was too large to fit into most boreholes. In spite of that, nine tracer tests have been conducted with several of these fluorometers online to monitor the water circulation in two test fields and one laboratory tank equipped with monitoring points. The instruments were set up close to the sampling wells. Peristaltic pumps, connected with plastic tubing to fluorometers were used to make the water from the well circulate through the optical cell of the instruments. During warm weather, the fluorescence was influenced by air bubbles generated by the ground water degassing when the water reached the surface. This behaviour is explained by the reduction of hydrostatic pressure which, in turn, allows dissolved air to escape at the surface. However, this degassing was able to be overcome by having the water flow through a mechanical degasser developed for our joint field use by ETH-Zurich.

Recently, we have revised the design using smaller optical parts allowing us to drastically reduce the size of the fluorometer so that it can go down 3" boreholes. A related advantage was that tracer tests could be performed under sub-zero temperature conditions since the water no longer needs to be brought to the surface but can be directly analysed with the fluorometer in place at the required formation depth.

The principal objective in the design of a new field fluorometer is to replace outdated and frequently impractical mechanical sampling systems. Three advantages favouring the use of field fluorometers are:

- Unlike mechanical water samplers, fluorometers have no moving parts, and therefore do not wear out.
- The signal sensor is always completely immersed removing the risk of freezing and ambient air change affects on the measurements.
- Unattended measurements with a high sampling frequency can extend over weeks instead of the daily or hourly sampling and the related 24- to 48-bottle limitation that frequently limits mechanical device measurement programs.

One of two sampling rates are available according to the programme objectives. The first rate has a measurement every 4 minutes. Between samples, the system is in standby mode requiring little power. The second rate has 6 measurements per minute. This faster mode is well suited for the analysis of discrete samples in the laboratory, for periodic calibrations and the types of rapid-change events such as borehole dilution or response with short impulse duration tests, that can be best interpreted with a high time resolution. The 10 second data acquisition rate represents a major improvement over mechanical samplers. They permit detection of rapid variations in dye concentration which can reflect aquifer heterogeneity. Also, for longer tests, the tracer arrival and maximum concentration peak can be defined with a precision of 4 minutes.

With mechanical samplers, small bottles are filled periodically. These bottles must be removed from the site at the end of each series. This operation is always quite error prone with the potential risk of contamination even when great care is taken. Once at the laboratory, the samples must be analysed, invoking additional costs and time delays. Moreover, the storage of the samples prior to their analysis can lead to variations in the dye concentration. For tracer experiments using several dyes, chemical cross-reactions may also occur. These disadvantages are avoided with the use of a field fluorometer.

The fluorometer probe (Fig. 1) connects to a water-resistant datalogger through a signal cable that can be up to 50 m long. The datalogger waterproof housing contains one or two rechargeable batteries providing the capacity for 2 to 4 weeks of unattended recording and the digital circuitry. The data is written to a rugged PCMCIA memory card with PC-interface compatibility. Other characteristics are in Table 1.

- Usable tracers	: uranine, sulforhodamine. Others
- Number of channels	: 4, including turbidity measurement 0.02 - 400 NTU
- Sensitivity	: ~ 500 mV per 10^{-7} g/ml
- Detection threshold	: 5 x 10^{-11} g/ml
- Saturation level	: 2 x 10^{-6} g/ml, adjustable internally
- Signal noise	: 0.1 mV
- Measuring intervals	: 10 seconds and 4 minutes
- Capacity of memory card	: 5123 samples (on SRAM 64kB PCMCIA)
- Recording time	: 14 to 28 days (with 1 or 2 batteries)
- ADC conversion dynamics	: 16 bits unipolar
- Data storage / transfer	: on PC memory card / direct connect. via serial port
- Power supply	: 12 Volt
- Battery capacity	: 7 to 14 Ah
- Stand-by consumption	: 5 mA with lamp off / 50 mA on
- Connections	: 20 m cable with one waterproof connector
- Weight (in working order)	: probe: 2 kg cable: 2.5 kg datalogger (1 battery): 6 kg

Table 1. Principal characteristics of the borehole fluorometer

It is often useful to inject different tracers from two locations during the same tracer test, for example to locate different pathways flowing to a spring or pumping well. By using different tracers at each injection site, the tracer data for each channel (*u, s*) are obtained subsequently, by processing the signals of the two receiving channels with the equation set

$$[u] = \frac{c_{22}x_1 - c_{12}x_2}{c_{11}c_{22} - c_{12}c_{21}} \qquad [s] = \frac{c_{11}x_2 - c_{21}x_1}{c_{11}c_{22} - c_{12}c_{21}} \qquad .$$

Two coefficients, c_{11} and c_{12} correspond to an excitation signal from source 1 of the uranine and sulforhodamine at a given concentration. Coefficients c_{21} and c_{22} correspond to source 2. The values x_1, x_2 are the voltages measured on the photodetectors. Using other fluorescent tracers is possible. However, to ensure good spectral separation, the optical filters must be chosen carefully, so that the denominator in the two equations does not vanish which would produce instabilities.

In conclusion, the borehole fluorometer is a versatile, economical instrument. It makes the field work of the hydrogeologist easier. Compared to mechanical samplers, it has the advantages of first, dramatically reduced surveillance and maintenance, and second, greater versatility for longer term, more rapid and even real time data acquisition and observation. With enhanced time resolution, this tool can now assist identifying the nature and extent of hydrogeological heterogeneity that previously was not possible. The results of tracer experiments can be seen 'as they happen' and used immediately. Finally, laboratory delay and expense, other than for confirmation samples, are dramatically reduced.

Reference

Schnegg, P.-A. and Doerfliger, N., 1997. *An inexpensive flow-through field fluorometer. Proc. of the 6th Conference on Limestone Hydrology and Fissured Media*, la Chaux-de-Fonds, Switzerland, August 1997, pp.47-50.

Figure 1. Borehole fluorometer probe