

# Tracers in Hydrology

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# Tracers in Hydrology

## III. Planning and experimental design

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1. Planning an experiment
2. Tracing surface water – discharge measurement + hydrograph separation (basin outflow)
3. Tracing the unsaturated zones (recharge studies)
4. Tracing ground water
5. Tracing surface-groundwater systems

### Competence, capacities

- Chose the right tracers for your specific study
- Define a tracer design
- Calculate the tracer amount
- Estimate the travel time and concentration
- Carry out the injection
- Plan the sampling
- Measure the tracer

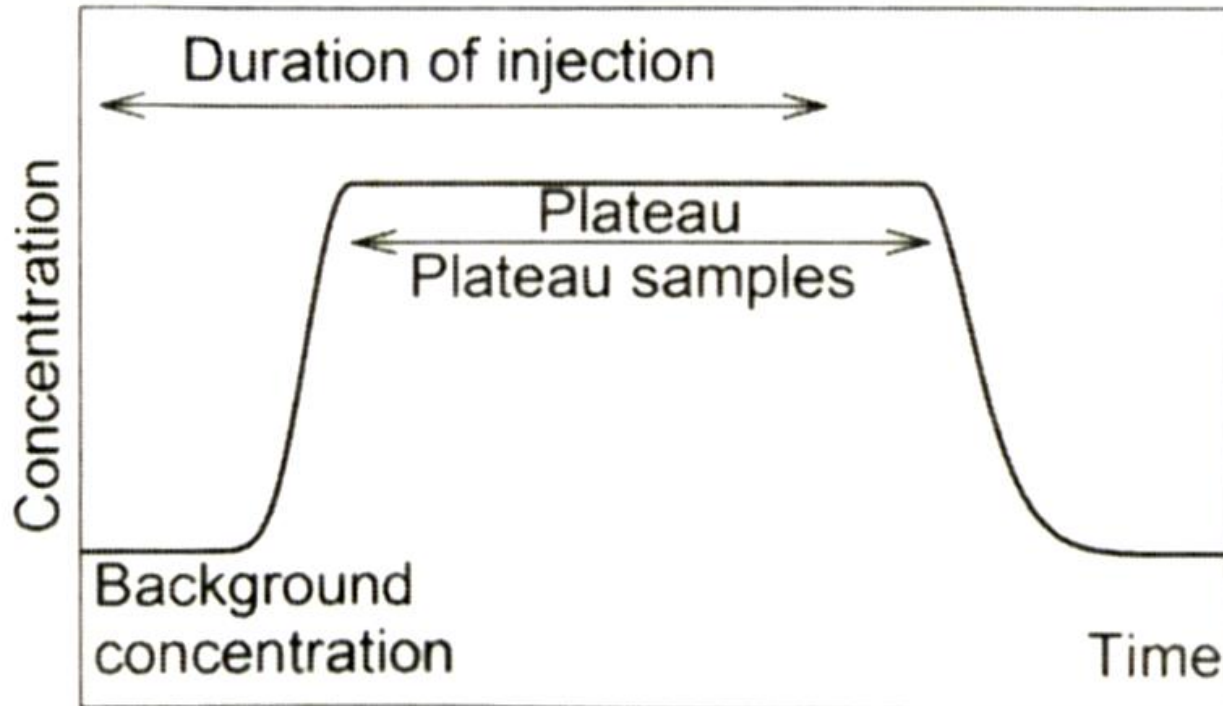
# Discharge Measurement

The resulting tracer breakthrough curve measured downstream arises typically from a background concentration to a constant value called the plateau concentration (Figure 1). Sampling is only permitted after the tracer has fully reached the constant plateau value at the end of the mixing section. One should remember that to obtain the plateau concentration downstream, the duration of pulse injection ( $T_{\text{pulse}}$ ) has to be sufficiently long. The discharge is calculated as:

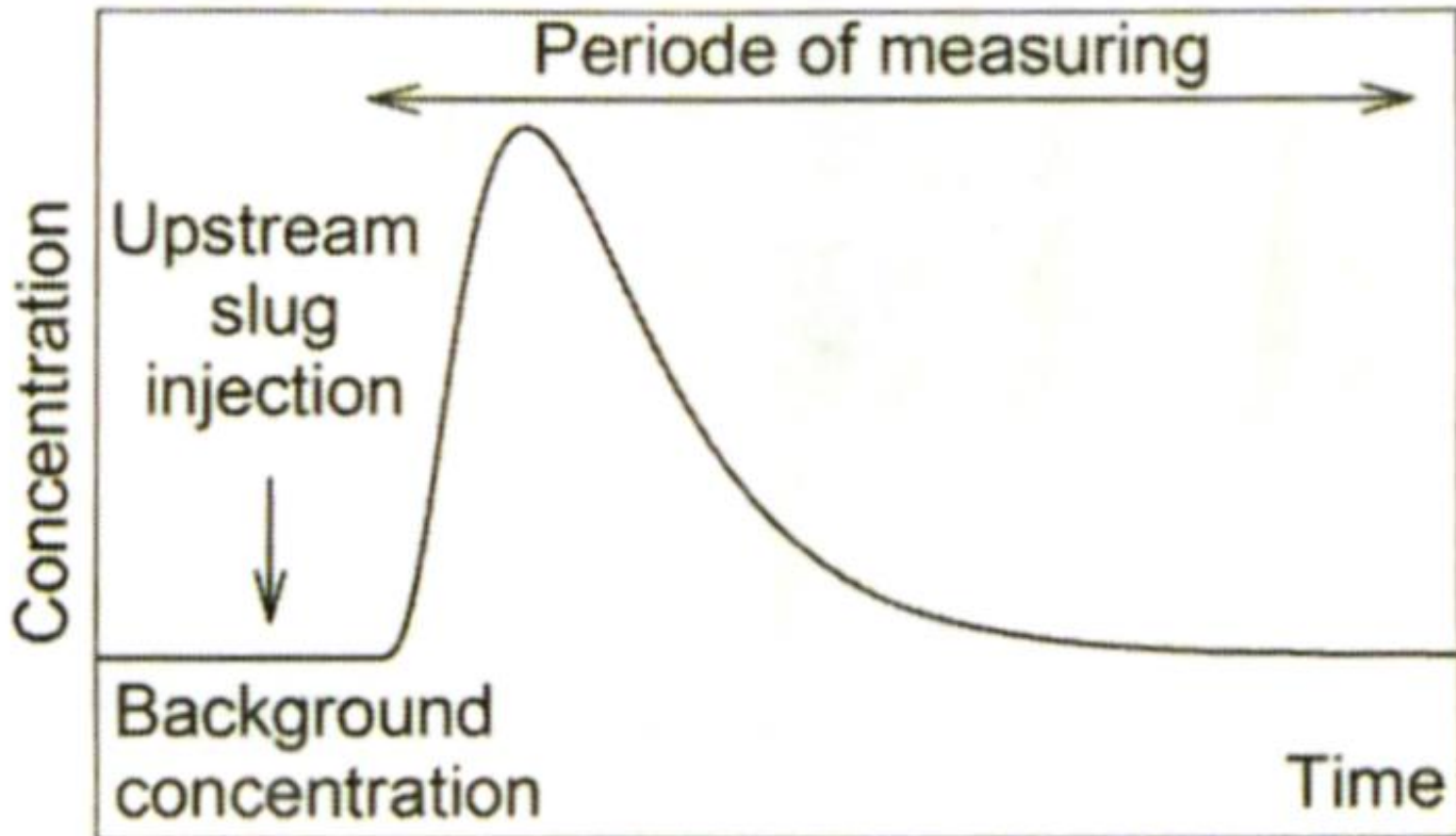
$$Q = \frac{q_{in} * (c_{in} - c_b)}{(c_p - c_b)}$$

with  $q_{in}$  tracer solution inflow rate (l/s)  
 $c_{in}$  tracer solution concentration (g/l)  
 $c_p$  measured sustained 'plateau' concentration (g/l)  
 $c_b$  background concentration (g/l)

# Discharge Measurement



# Discharge Measurement



# Discharge Measurement

$$Q = \frac{M}{\int_0^{\infty} (c(t) - c_b) dt}$$

with  $M$  injected tracer mass (g)

$c(t)$  measured concentration at time,  $t$

$c_b$  background concentration

# Discharge Measurement

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$c(t)$  measured concentration at time,  $t$

$c_b$  background concentration

# Discharge Measurement

$$Q = \frac{M}{\sum_i^N (c_i - c_b) \Delta t_i}; \quad i - \text{samples}$$

with  $c_i$

$\Delta t_i = (t_{i+1} - t_i)$

N

measured concentration at time,  $t_i$

time interval between two collected samples

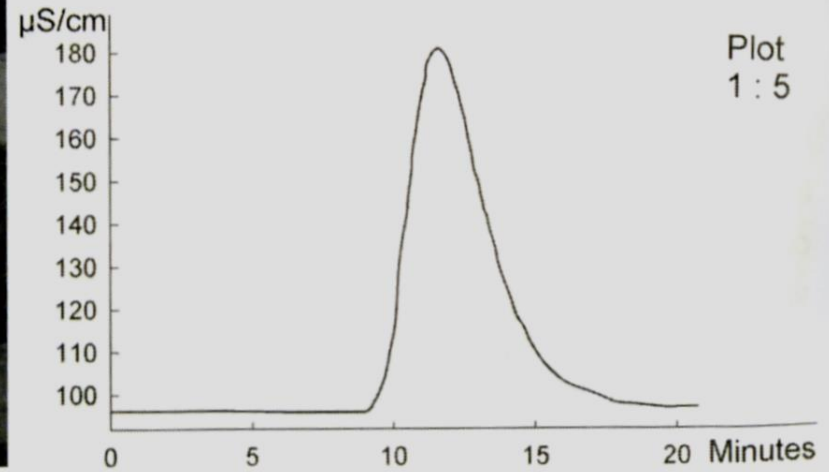
amount of samples



# Discharge Measurement

	Advantage	Disadvantage
<i>Using salt tracer</i>		
Slug injection	<ul style="list-style-type: none"> <li>– Short measuring time</li> <li>– Direct calculation in situ</li> </ul>	<ul style="list-style-type: none"> <li>– Only small discharge measurable</li> <li>– High masses of tracer needed due to usually high background concentrations</li> </ul>
Constant rate injection	<ul style="list-style-type: none"> <li>– May be also achieved with simple techniques</li> <li>– Rather cheap equipment</li> </ul> <p>not recommended for salt tracers</p>	
<i>Using fluorescent tracer</i>		
Slug injection	<ul style="list-style-type: none"> <li>– High discharge measurable</li> <li>– Small amount of tracer</li> <li>– Short measuring time</li> <li>– High discharge measurable</li> <li>– High accuracy</li> </ul>	<ul style="list-style-type: none"> <li>– Accuracy may be affected by sorption effects on suspended load</li> <li>– Accuracy may be affected by sorption effects on suspended load</li> <li>– Analysis in the laboratory if no field fluorometer is available</li> </ul>
Constant rate injection	<ul style="list-style-type: none"> <li>– Validation possible by repeat sampling</li> </ul>	<ul style="list-style-type: none"> <li>– Photolytical decay of tracers</li> <li>– Long measuring time</li> <li>– More tracer needed</li> <li>– Higher effort required for preparation of experiment</li> </ul>

# Discharge Measurement



# Discharge Measurement

The experiment was carried out in clear river water using Uranine. As expected, the background concentration ( $c_b$ ) was zero, as Uranine is not part of chemical compositions of natural waters. The tracer breakthrough was sampled at constant time intervals of exactly  $\Delta t = (t_{i+1} - t_i) = 20$  s and analysed in the laboratory (Figure 6.13).

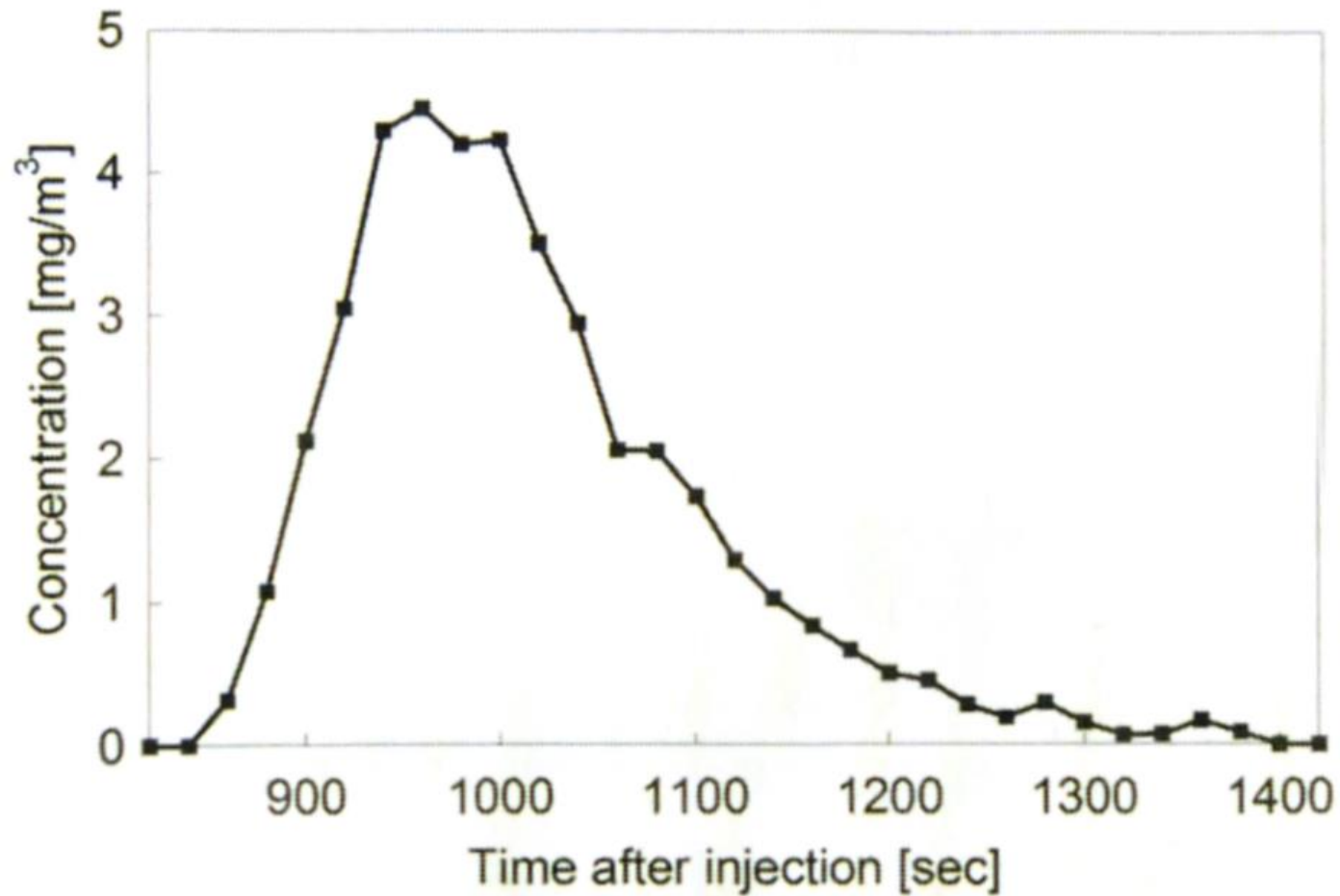
The injected tracer mass was  $M = 1$  g Uranine. Altogether 27 samples were taken. According to Equation (6.9), the discharge is calculated as follows:

$$Q = \frac{M}{\sum_i (c_i \times \Delta t)} = \frac{1000000 \mu\text{g}}{20\text{s} \times \sum_i c_i}$$

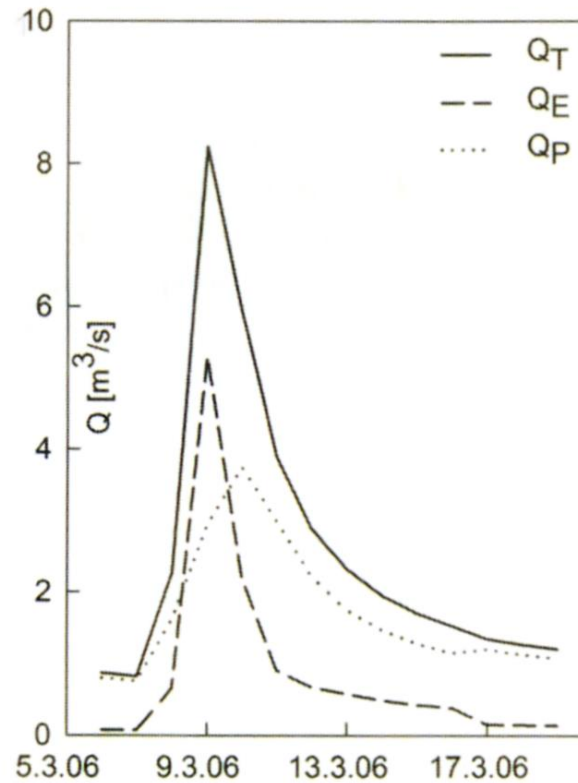
The sum of all products of measured concentrations ( $\sum c_i \times \Delta t$ ) is  $843.24 [\mu\text{g} \times \text{s}/\text{l}]$ , which yields the discharge of:

$$Q = \frac{1000000 \mu\text{g}}{843.24 \mu\text{g}/\text{l}/\text{s}} = 1186 \text{ l}/\text{s} \approx 1.2 \text{ m}^3/\text{s}.$$

# Discharge Measurement



# Hydrograph Separation



**Figure** ... Example for a hydrograph separation in event and pre-event water.  $Q$  = discharge and  $C = \delta^{18}\text{O}$  content of E = Event water, P = Pre-event water.

# Hydrograph Separation

Date	Measured		Calculated	
	$Q_T$ [m <sup>3</sup> /s]	$C_T$ [‰ V-SMOW]	$Q_E$ [m <sup>3</sup> /s]	$Q_P$ [m <sup>3</sup> /s]
6/3/2006	0.87	-9.78	0.05	0.82
7/3/2006	0.82	-9.78	0.05	0.77
8/3/2006	2.27	-10.07	0.60	1.67
9/3/2006	8.27	-10.58	5.20	3.07
10/3/2006	5.93	-10.19	2.08	3.85
11/3/2006	3.89	-9.99	0.81	3.08
12/3/2006	2.88	-9.99	0.60	2.28
13/3/2006	2.32	-10.02	0.53	1.79
13/3/2006	1.95	-10.02	0.45	1.50
15/3/2006	1.70	-10.02	0.39	1.31
16/3/2006	1.53	-10.02	0.35	1.18
17/3/2006	1.35	-9.82	0.12	1.23
18/3/2006	1.27	-9.82	0.11	1.16
19/3/2006	1.21	-9.82	0.10	1.11

# Hydrograph Separation

Separation of total discharge in event and pre-event water: assumed event water input:  $C_E = -11.1\text{‰}$ , assumed pre-event water (after low-flow period):  $C_P = -9.7\text{‰}$

$$Q_T = Q_E + Q_P$$

$$Q_T * C_T = Q_E * C_E + Q_P * C_P$$

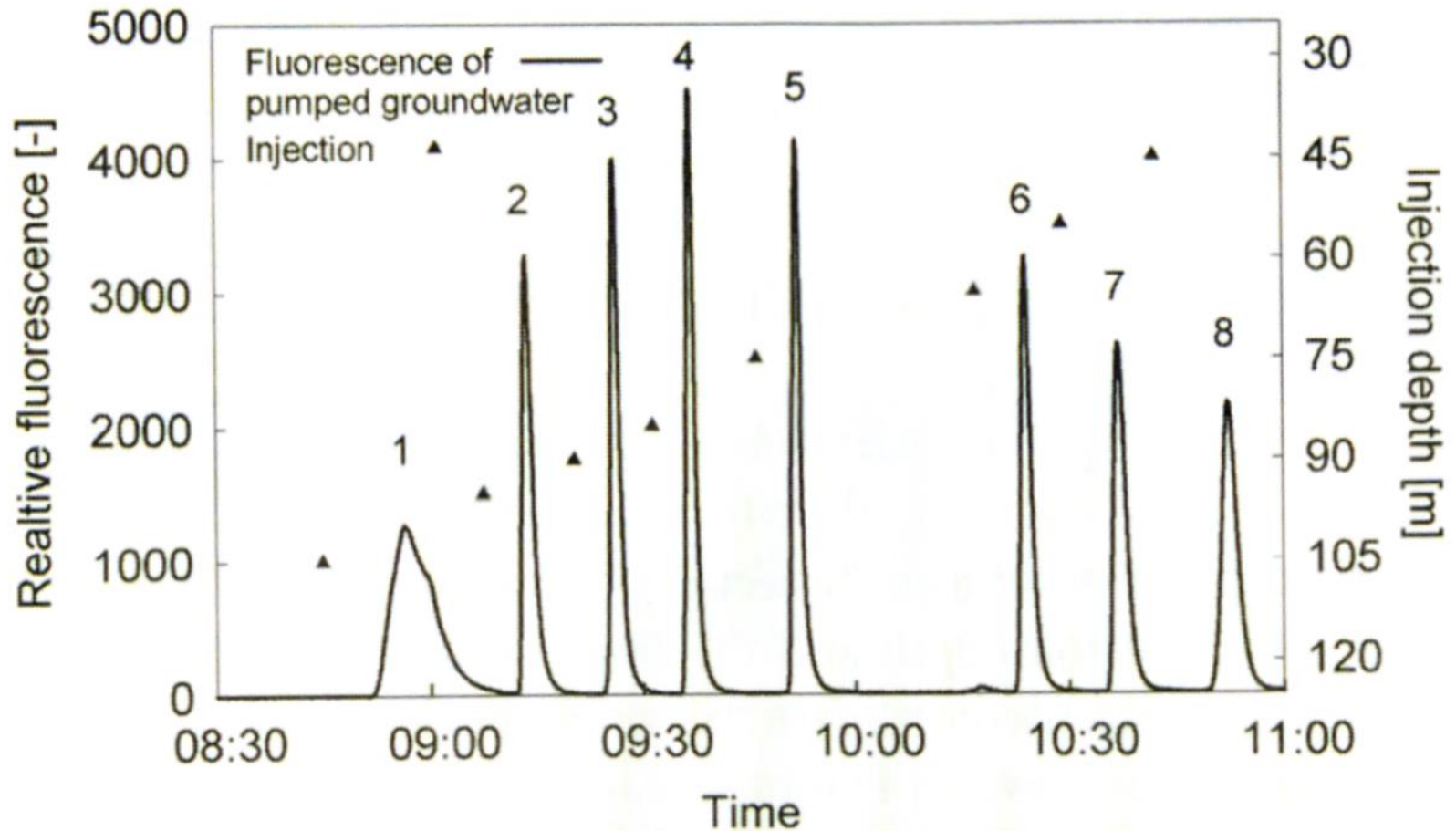
→

$$Q_E = Q_T \frac{C_T - C_P}{C_E - C_P}$$

$$Q_P = Q_T - Q_E$$

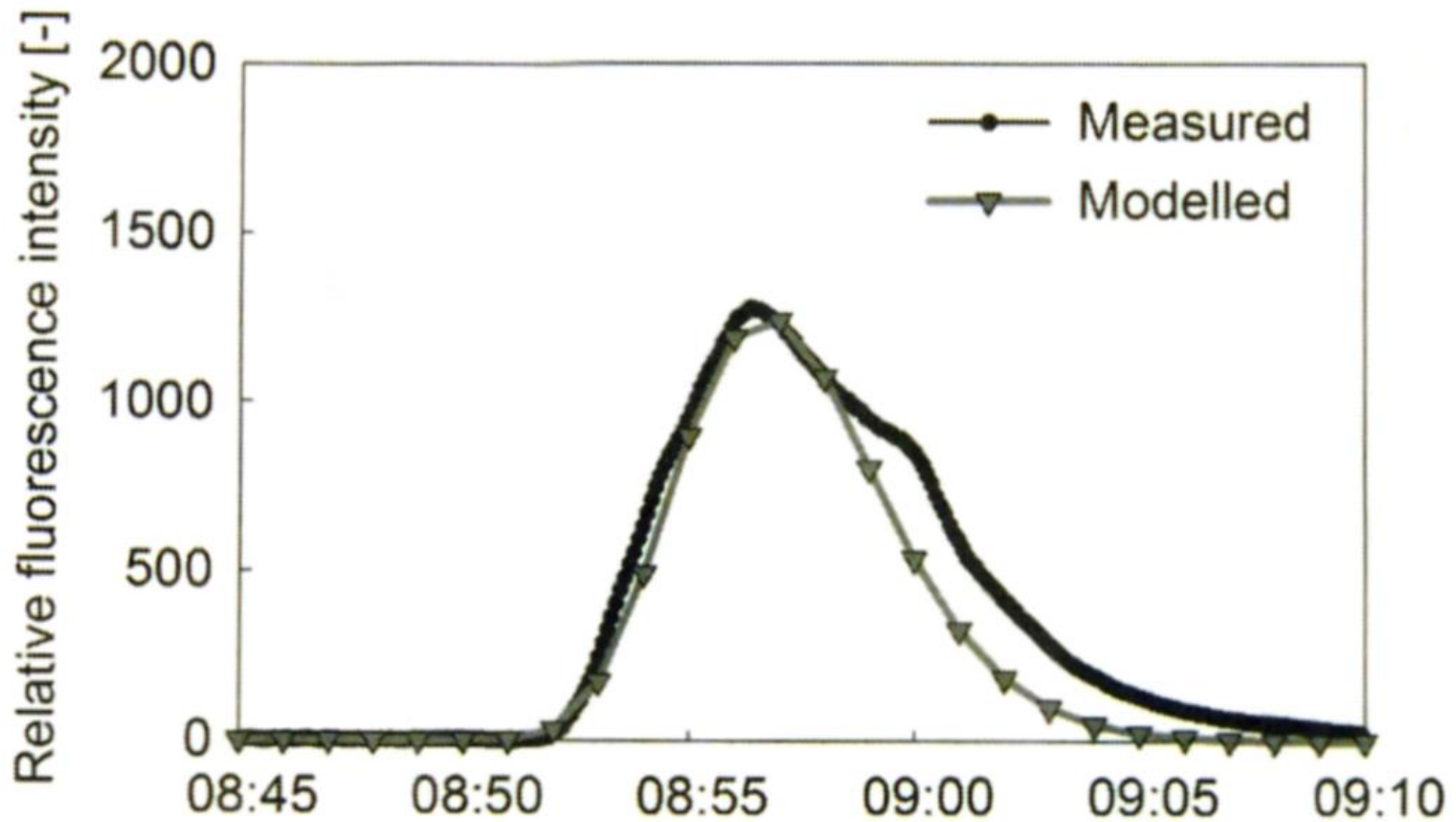


# Single Well tests





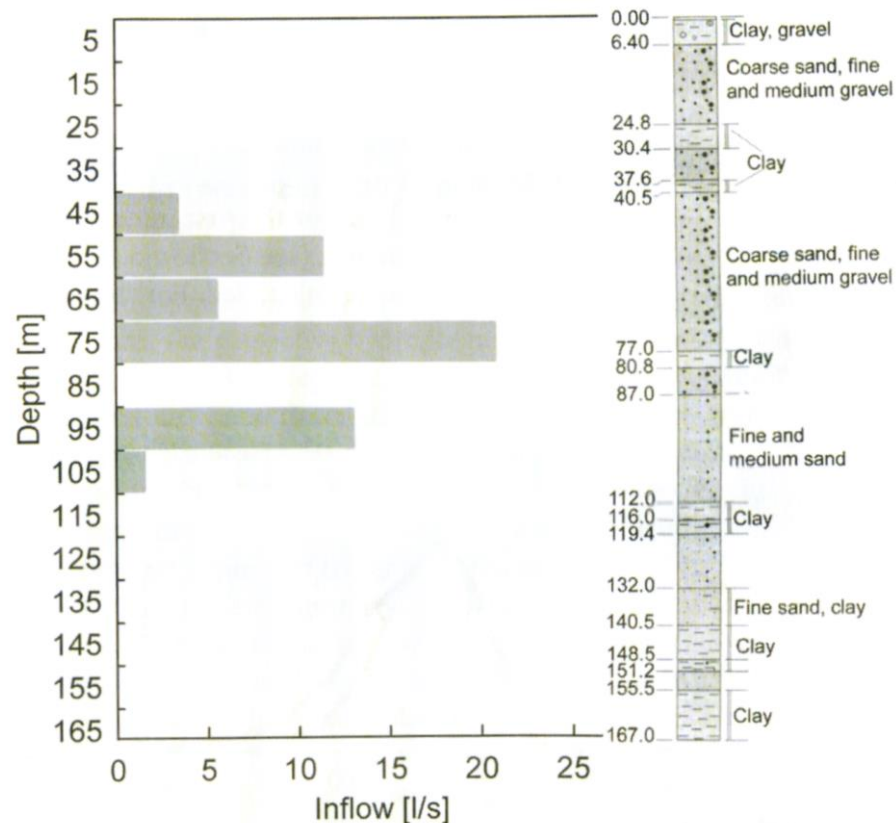
# Single Well tests



# Single Well tests

From the cross-section area  $A$  of the borehole given by  $\pi r^2$  ( $r$  = radius of the borehole), the travel time  $t'$  between injection and detection, and for the distance between the injection depth and the depth of the pump  $s$ , the discharge  $q$  can be calculated according to:

$$q = v_f A = \pi r^2 s / t'$$



# Single Well tests

The estimation of the filter velocity is carried out by measuring the dilution of tracer concentration  $c(t)$  in the well, as a function of time ( $t$ ). The tracer concentration is monitored continuously after the initial constant homogenous distribution of the injected tracer with the concentration  $c_0$  ( $t = 0$ ) is reached. The interpretation requires a stationary and horizontal groundwater flow through the filter pipe. These requirements are fulfilled for the tracer probe shown in Figure . The result of the measurement is a dilution log, in which the filter velocity  $v_f$  can be calculated from equation

$$v_f = \pi r \ln [c_0/c(t')]/(2\alpha t')$$

# Single Well tests

$$v_f = \pi r \ln [c_0/c(t')]/(2\alpha t')$$

where

$c_0$  = tracer concentration at  $t = 0$

$c(t')$  = tracer concentration at  $t'$

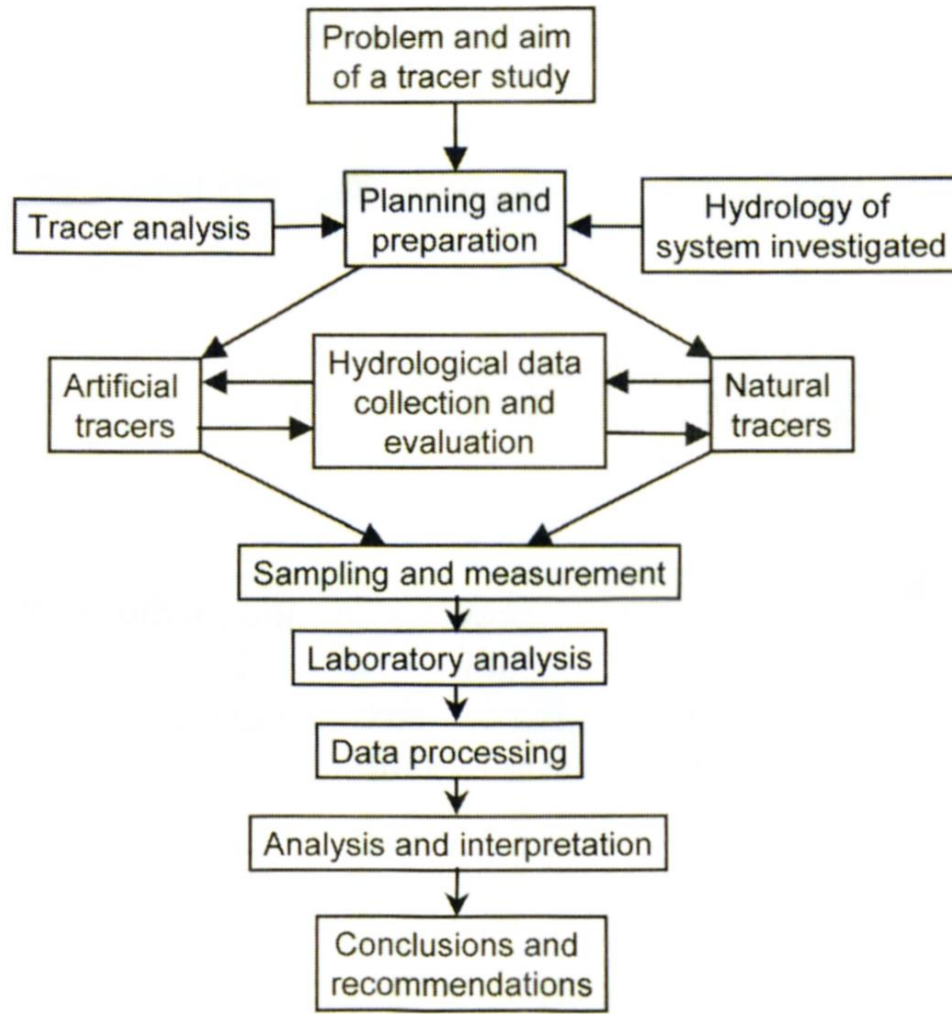
$r$  = inner radius of the filter pipe

$\alpha$  = correction factor ( $\sim 1.5-2.0$ )

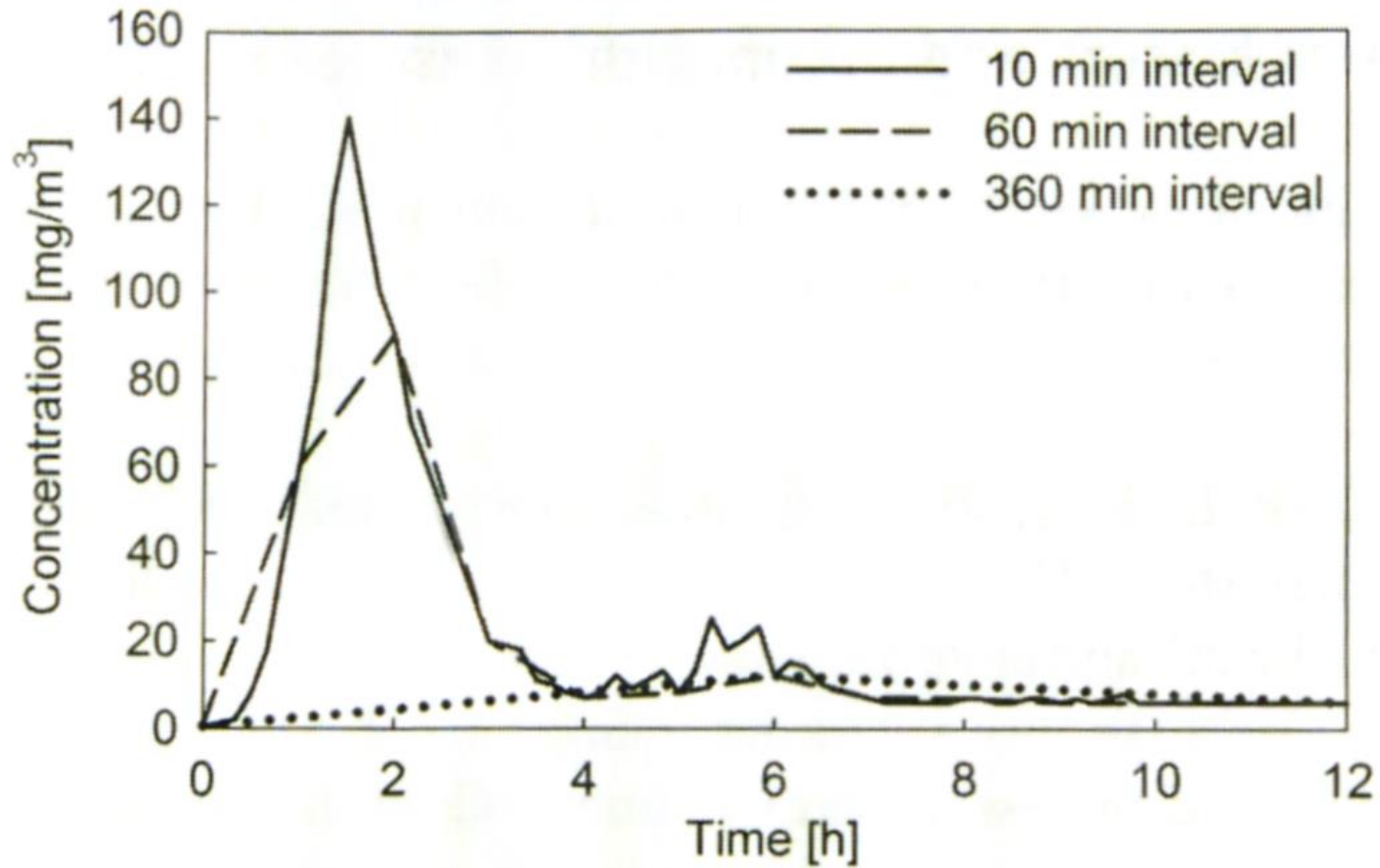
After finding the filter velocity and knowing the regional hydraulic gradient ( $i$ ) one can also easily approximate the hydraulic conductivity ( $k$ ) using Darcy's Law:

$$k = v_f / i$$

# Planing a Tracer Test

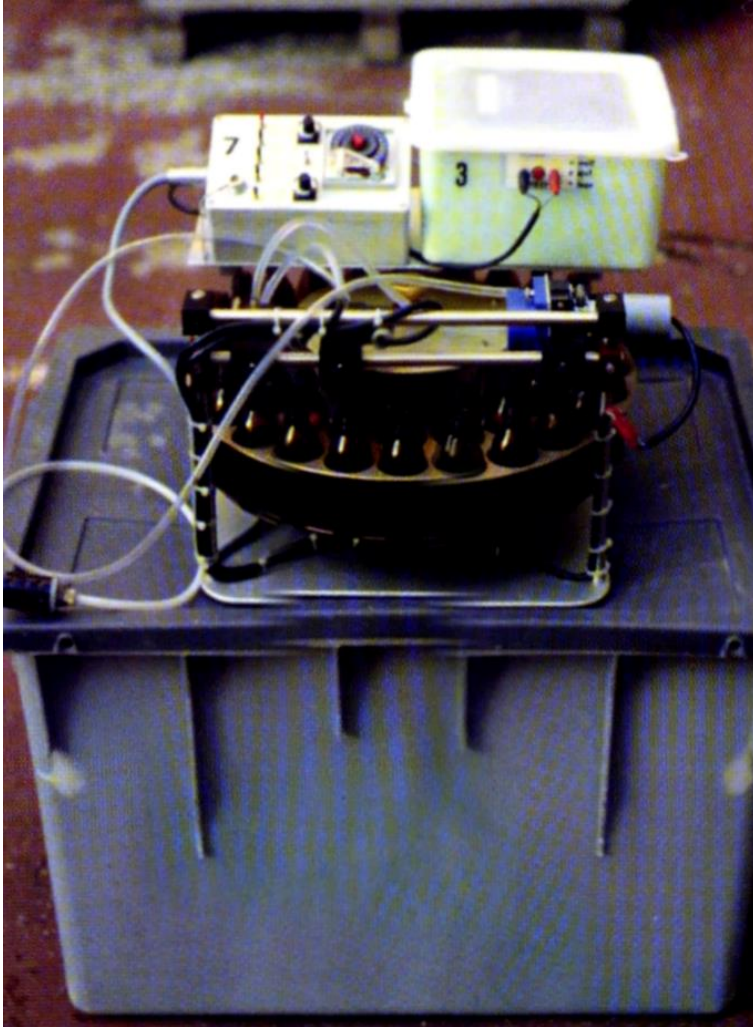


# Planing a Tracer Test





# Planing a Tracer Test



# Planing a Tracer Test

- the expected tracer breakthrough curve and the maximum concentrations corresponding sampling intervals;
- the sampling concept;
- the methods of analysis and interpretation;
- the potential risks and the contingency plans.



# Planing a Tracer Test

## Submission of assignments

- Saturday 24:00, email: [christoph.kuells@fh-luebeck.de](mailto:christoph.kuells@fh-luebeck.de) or [info@uhydro.de](mailto:info@uhydro.de)
- Assignment 1: about ½ page, written task, choice of tracer, justification
- Assignment 2: about ½ page, written with Excel table, task, choice of method, calculation, result, sensitivity
- Assignment 3: Plan for a tracer experiment, choice of tracer, calculation of amount, map (OpenStreetMap), distances, sampling locations, sampling intervals, + annexes (calculation of breakthrough curve)