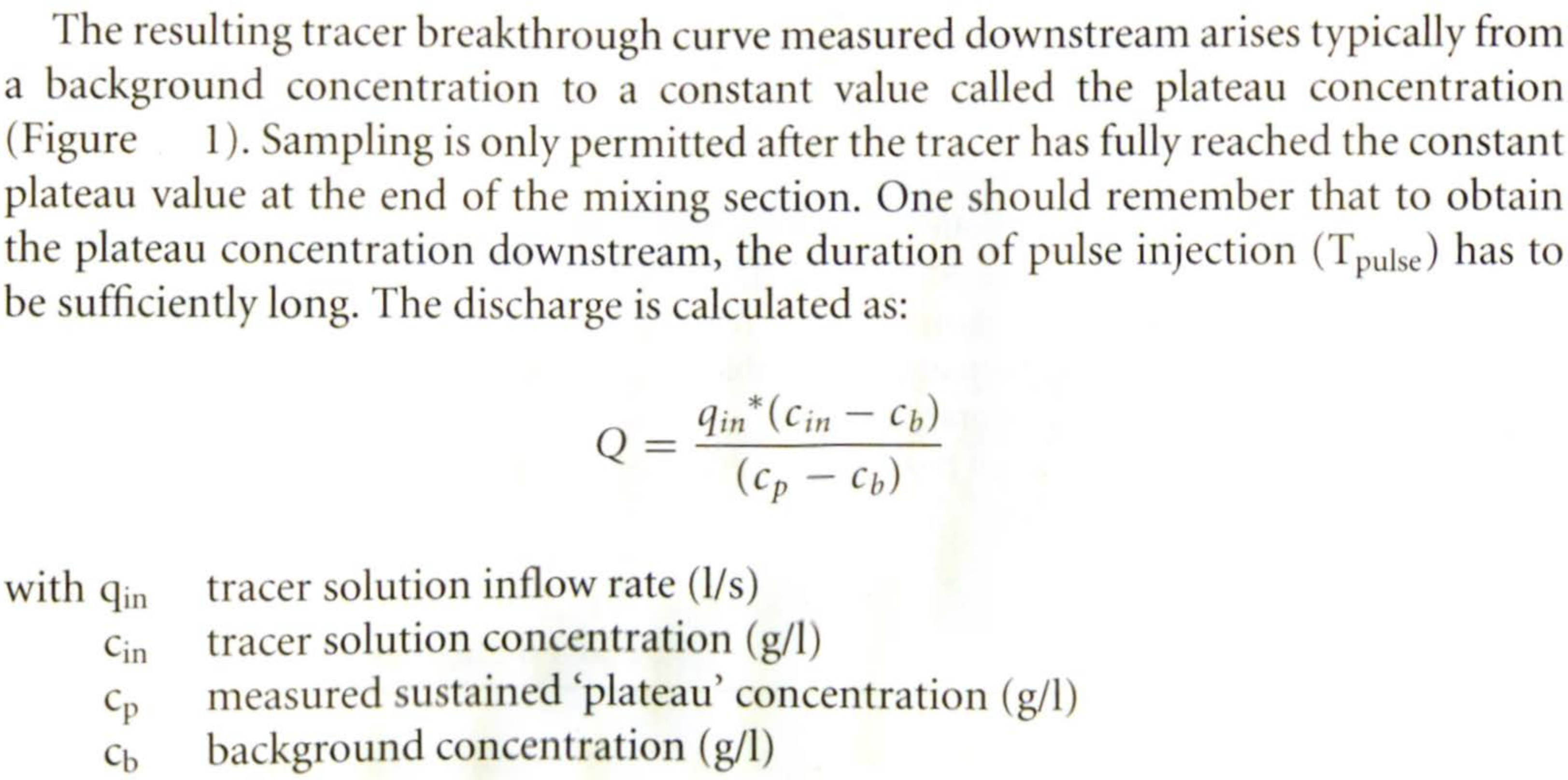
Tracers in Hydrology

Prof. Dr. Christoph Külls

Discharge Measurement

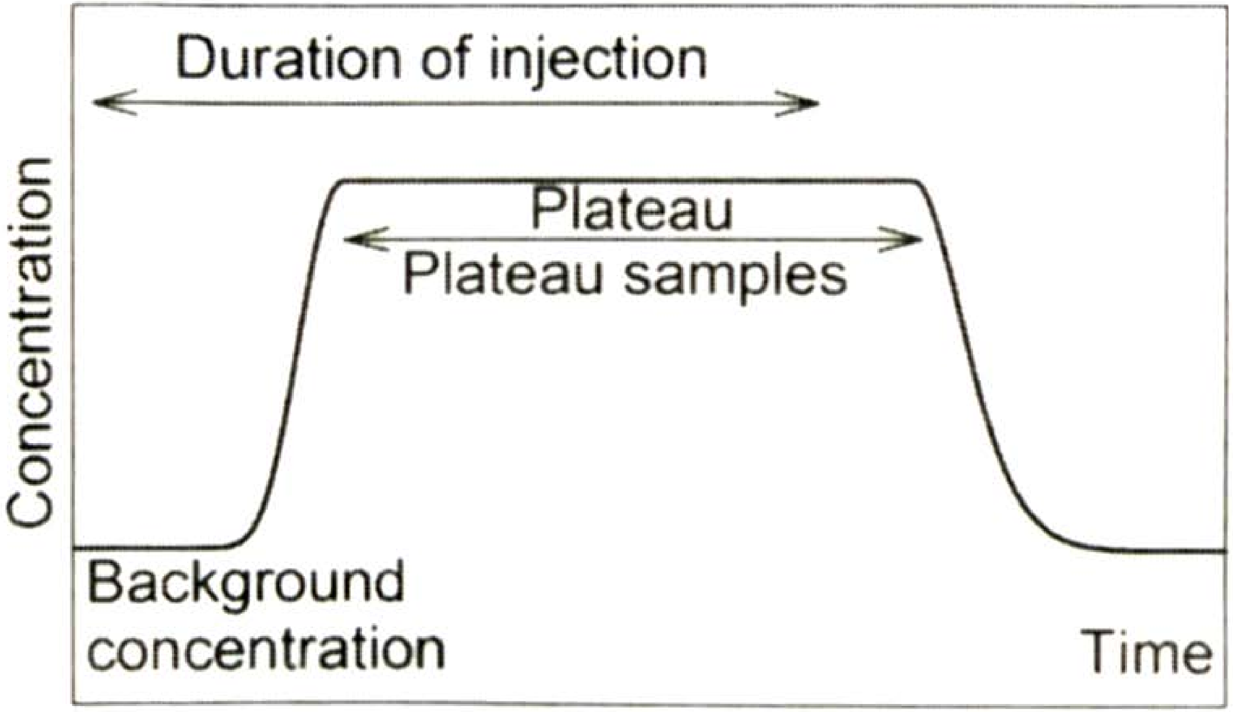


The resulting tracer breakthrough curve measured downstream arises typically from a background concentration to a constant value called the plateau concentration (Figure 1). Sampling is only permitted after the tracer has fully reached the constant plateau value at the end of the mixing section. One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



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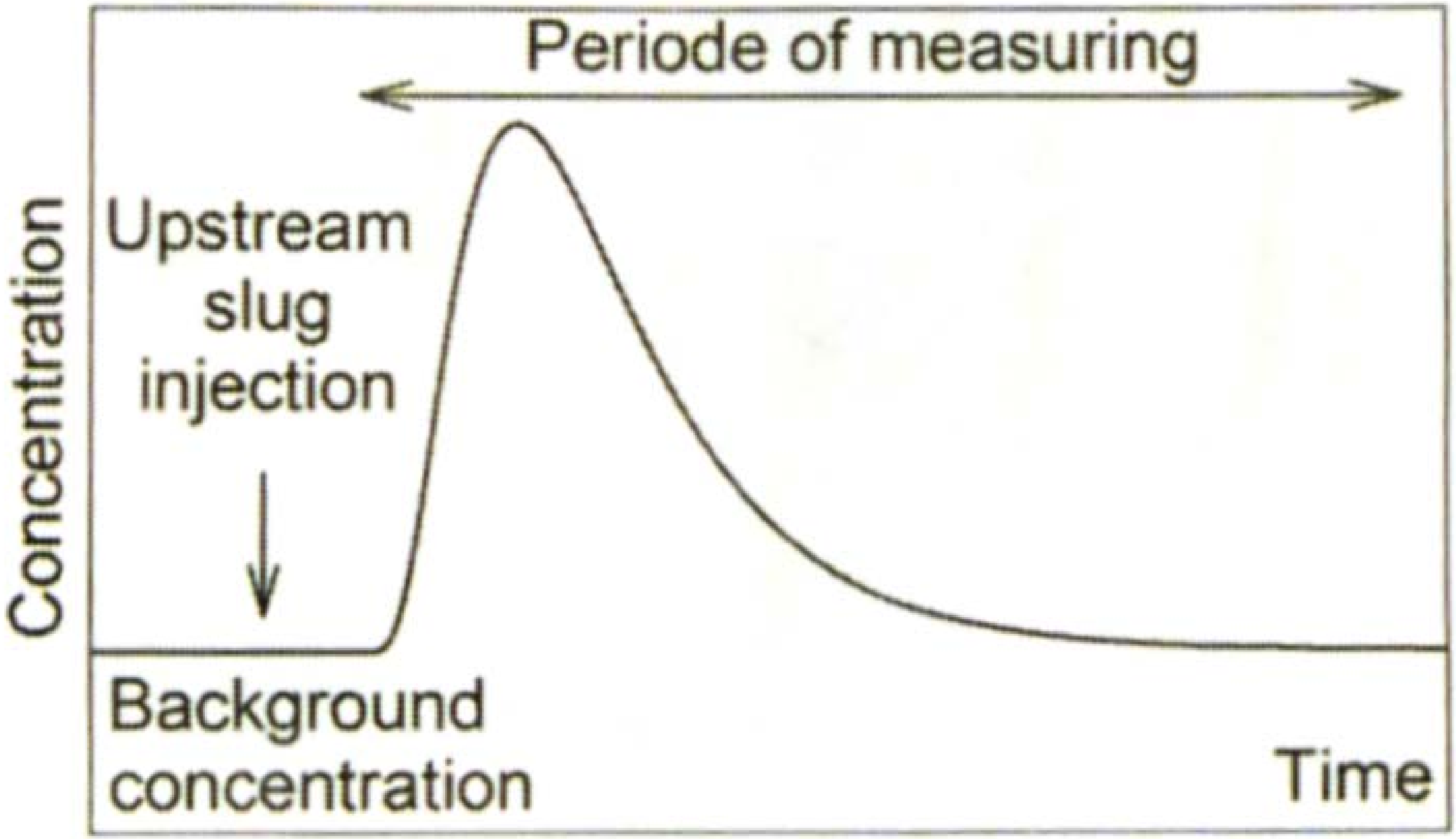

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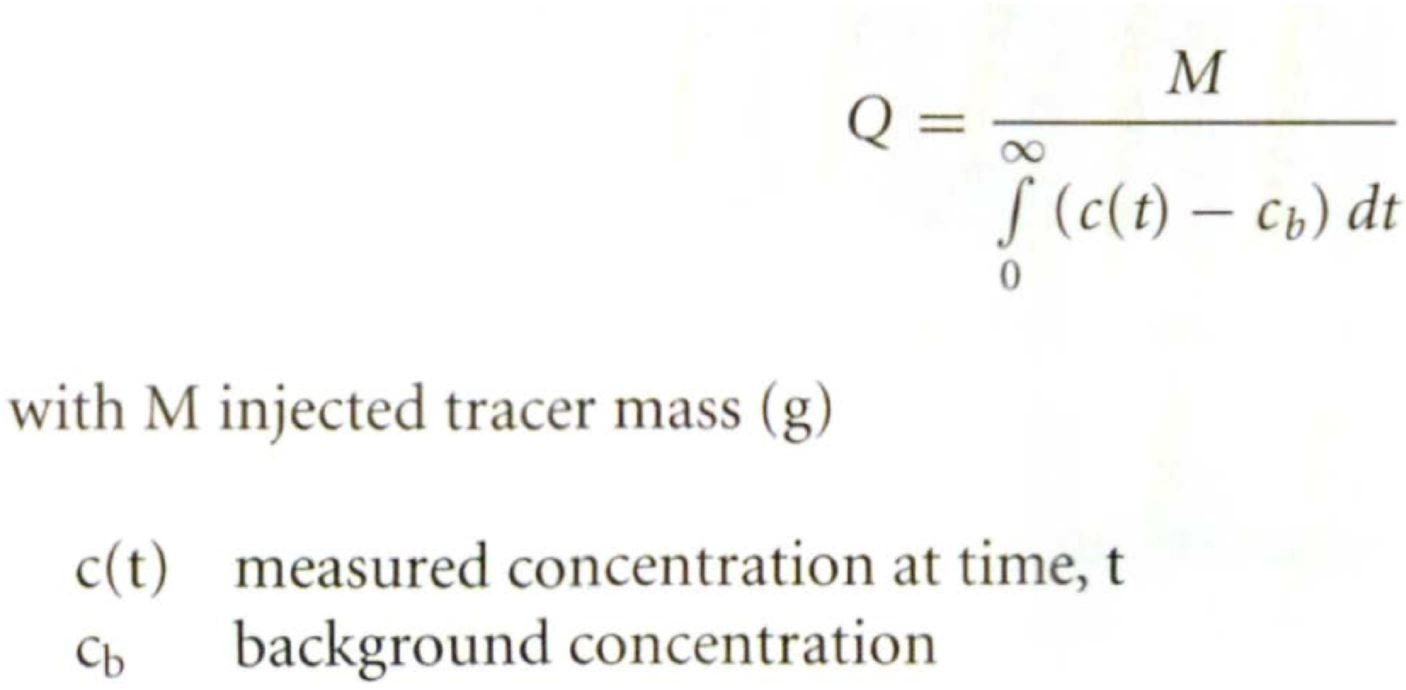


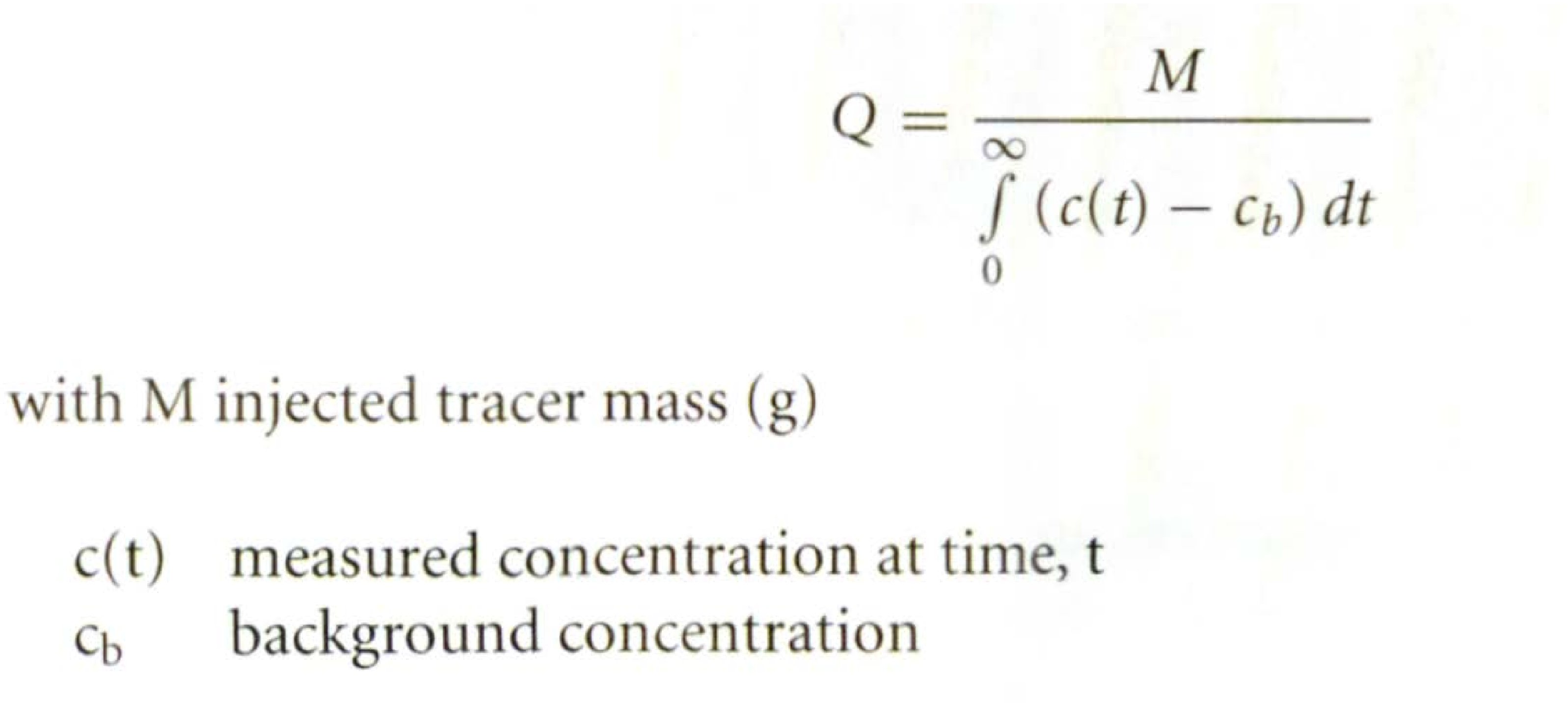
$$Q = \frac{M}{\int_0^\infty (c(t) - c_b)\, dt}$$

with M injected tracer mass (g)

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

c_b background concentration

Discharge Measurement

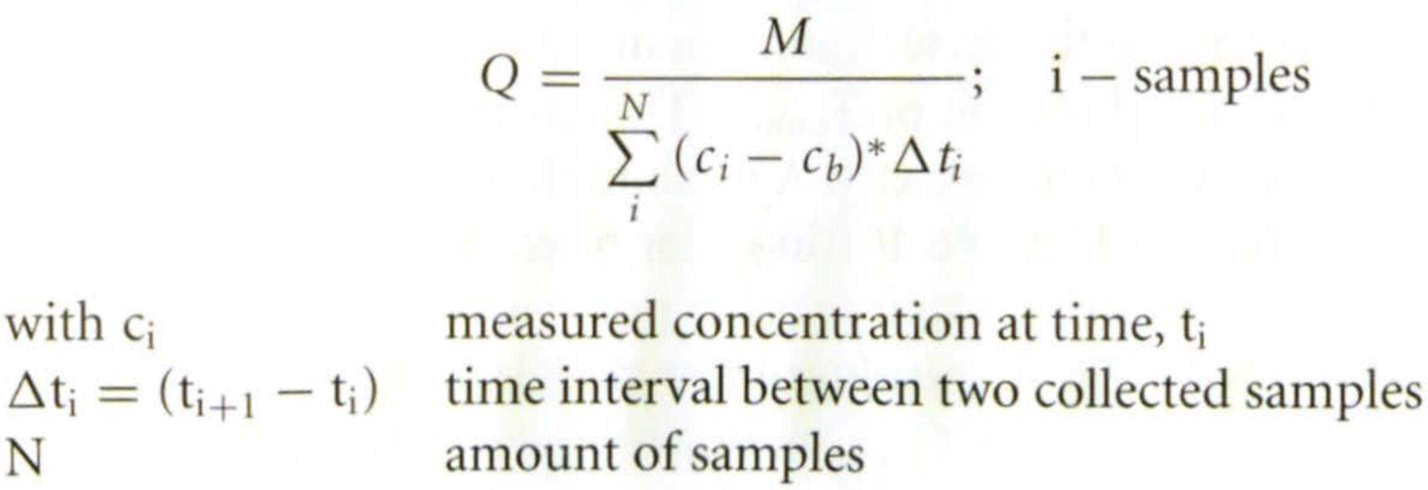


$$Q = \frac{M}{\int_0^{\infty} (c(t) - c_b)\, dt}$$

with M injected tracer mass (g)

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

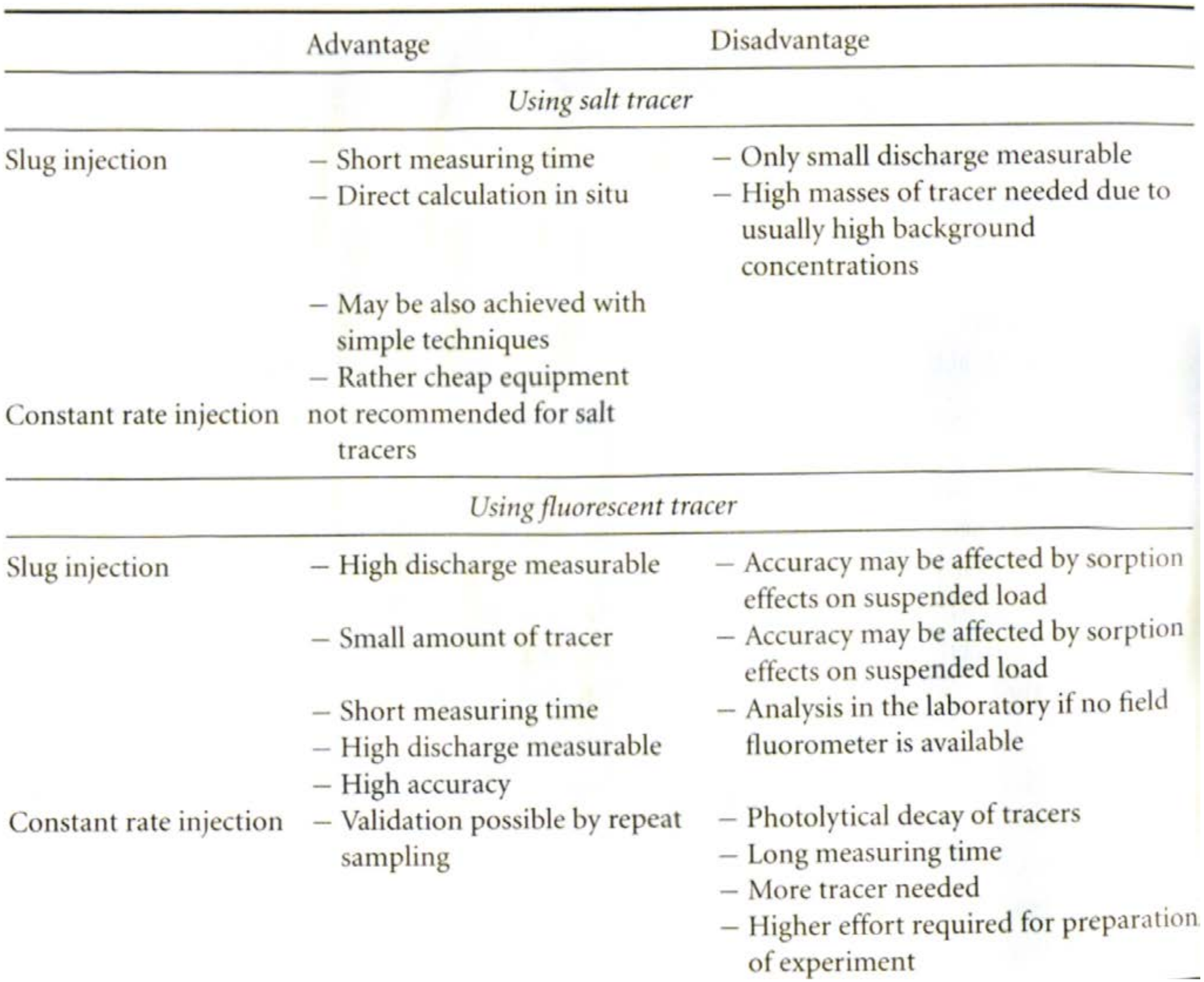
Discharge Measurement



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

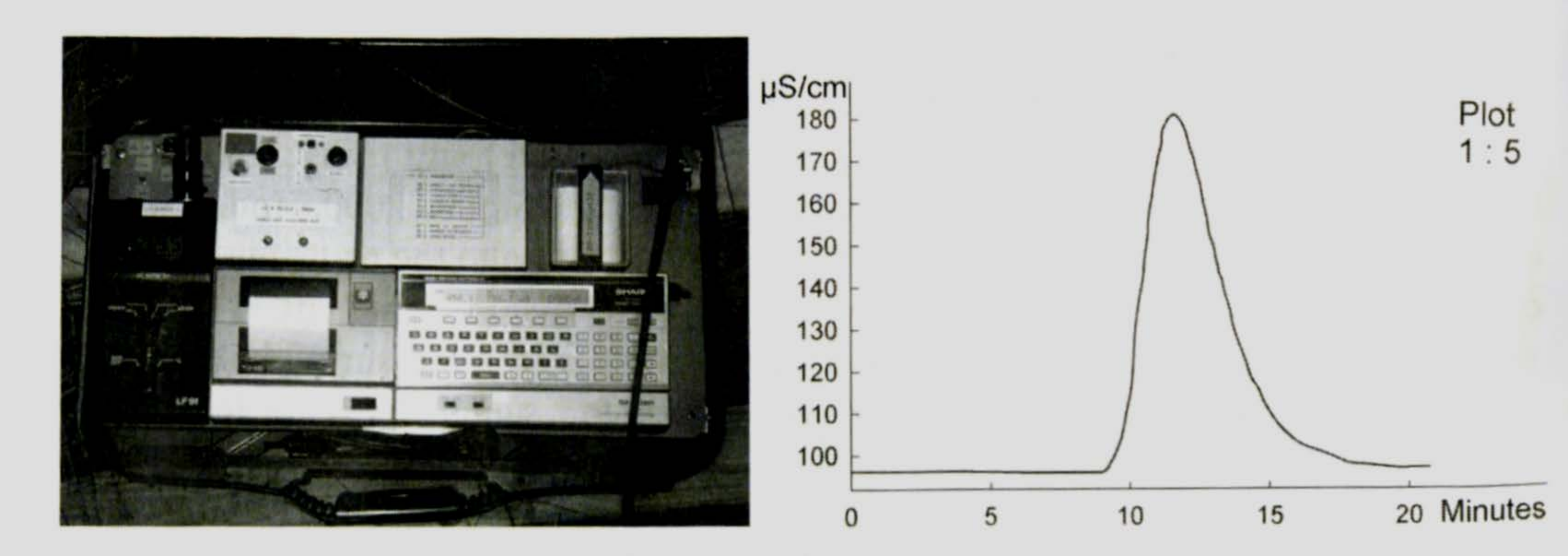
with c_i	measured concentration at time, t_i
$\Delta t_i = (t_{i+1} - t_i)$	time interval between two collected samples
N	amount of samples

Discharge Measurement

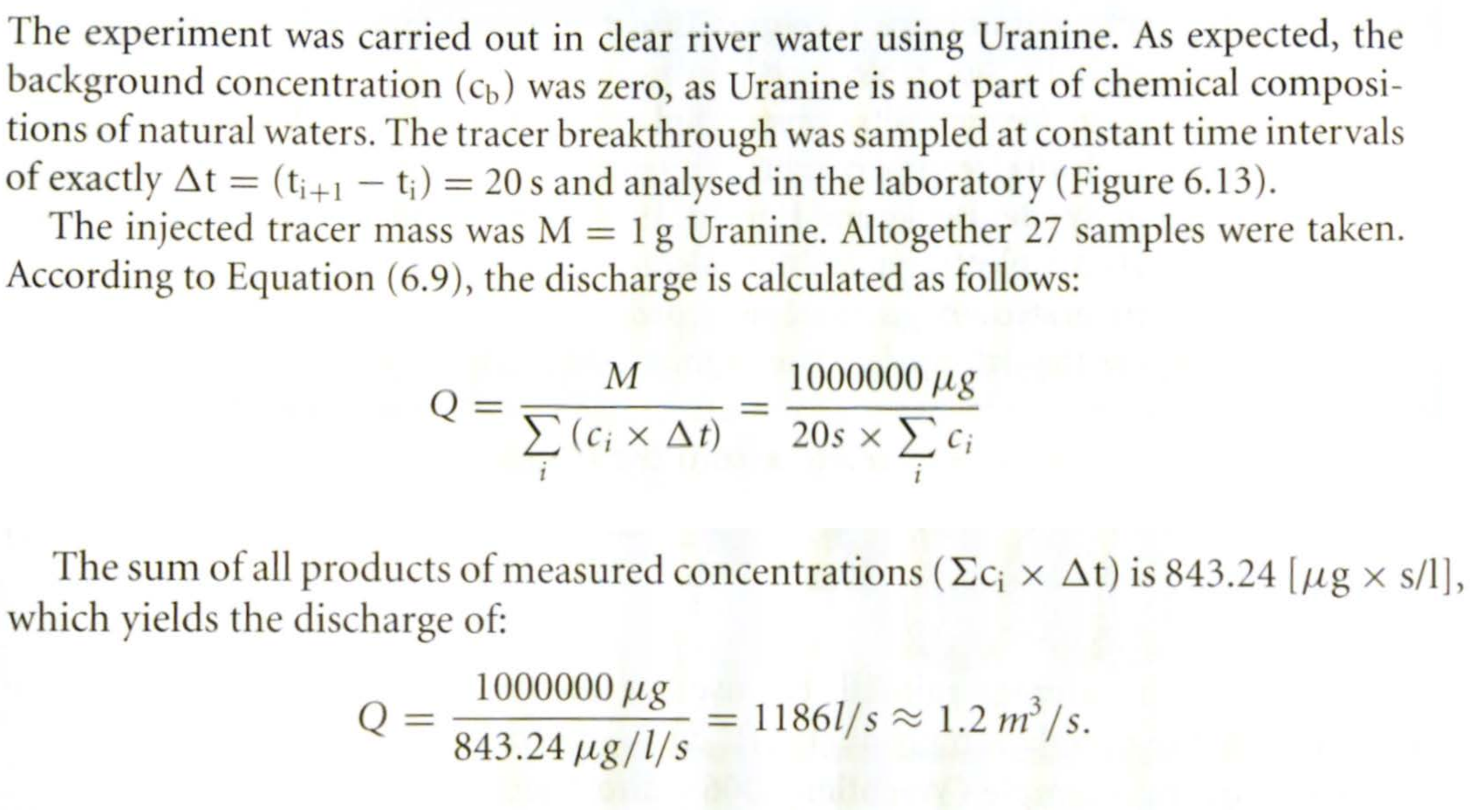


	Advantage	Disadvantage
	Using salt tracer	
Slug injection	– Short measuring time – Direct calculation in situ – May be also achieved with simple techniques – Rather cheap equipment	– Only small discharge measurable – High masses of tracer needed due to usually high background concentrations
Constant rate injection	not recommended for salt tracers	
	Using fluorescent tracer	
Slug injection	– High discharge measurable – Small amount of tracer – Short measuring time	– Accuracy may be affected by sorption effects on suspended load – Accuracy may be affected by sorption effects on suspended load – Analysis in the laboratory if no field fluorometer is available
Constant rate injection	– High discharge measurable – High accuracy – Validation possible by repeat sampling	– Photolytical decay of tracers – Long measuring time – More tracer needed – Higher effort required for preparation of experiment

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).

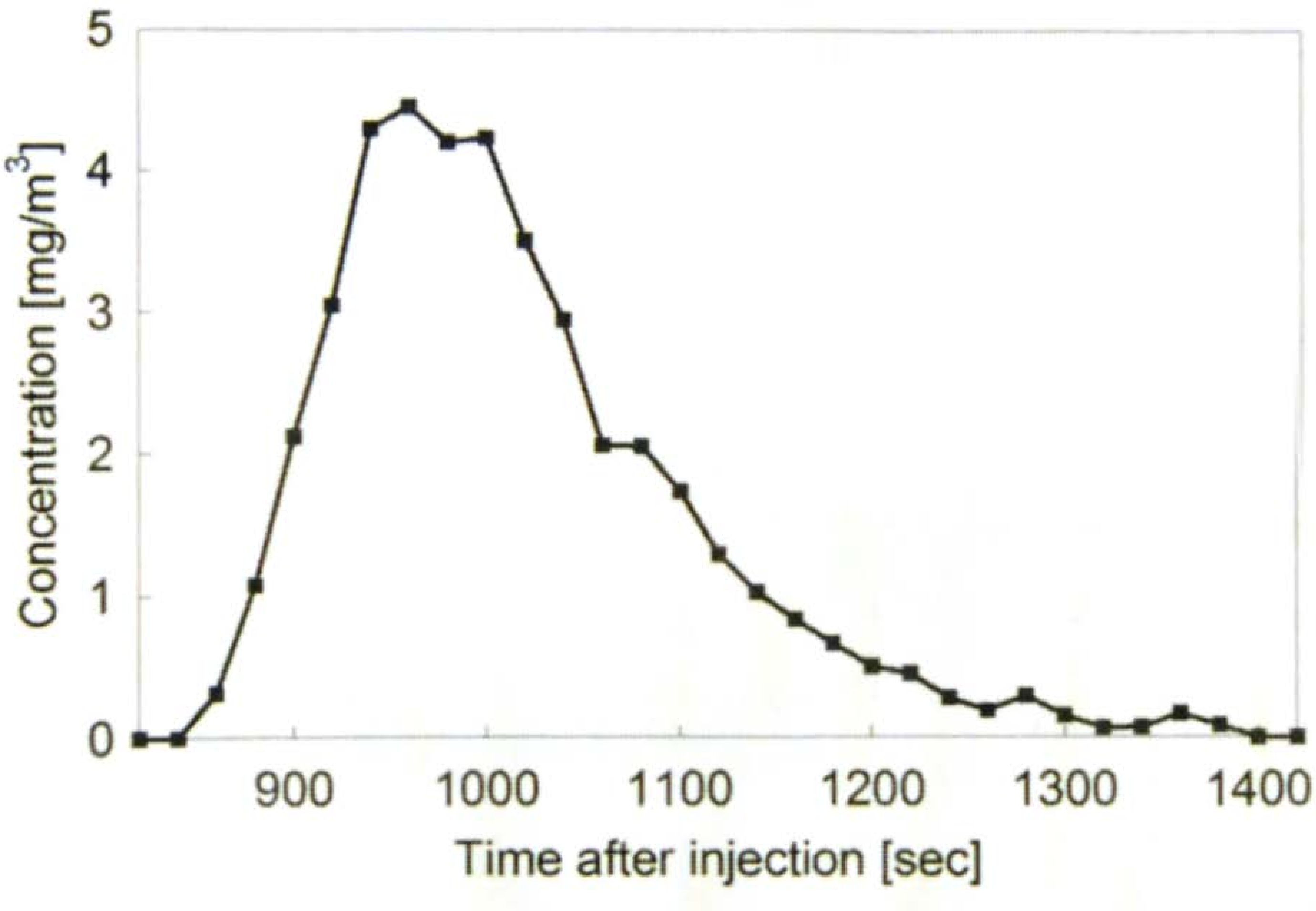
The injected tracer mass was M = 1 g Uranine. Altogether 27 samples were taken. According to Equation (6.9), the discharge is calculated as follows:

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

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

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

Discharge Measurement



Hydrograph Separation

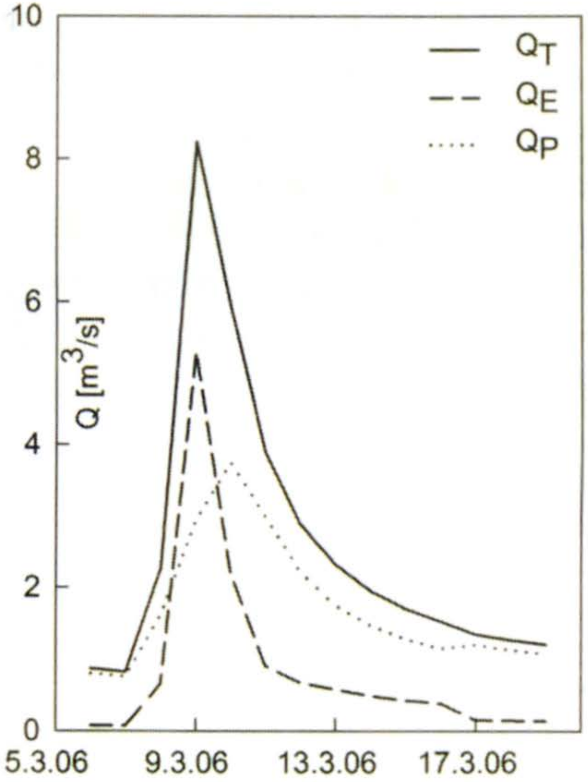
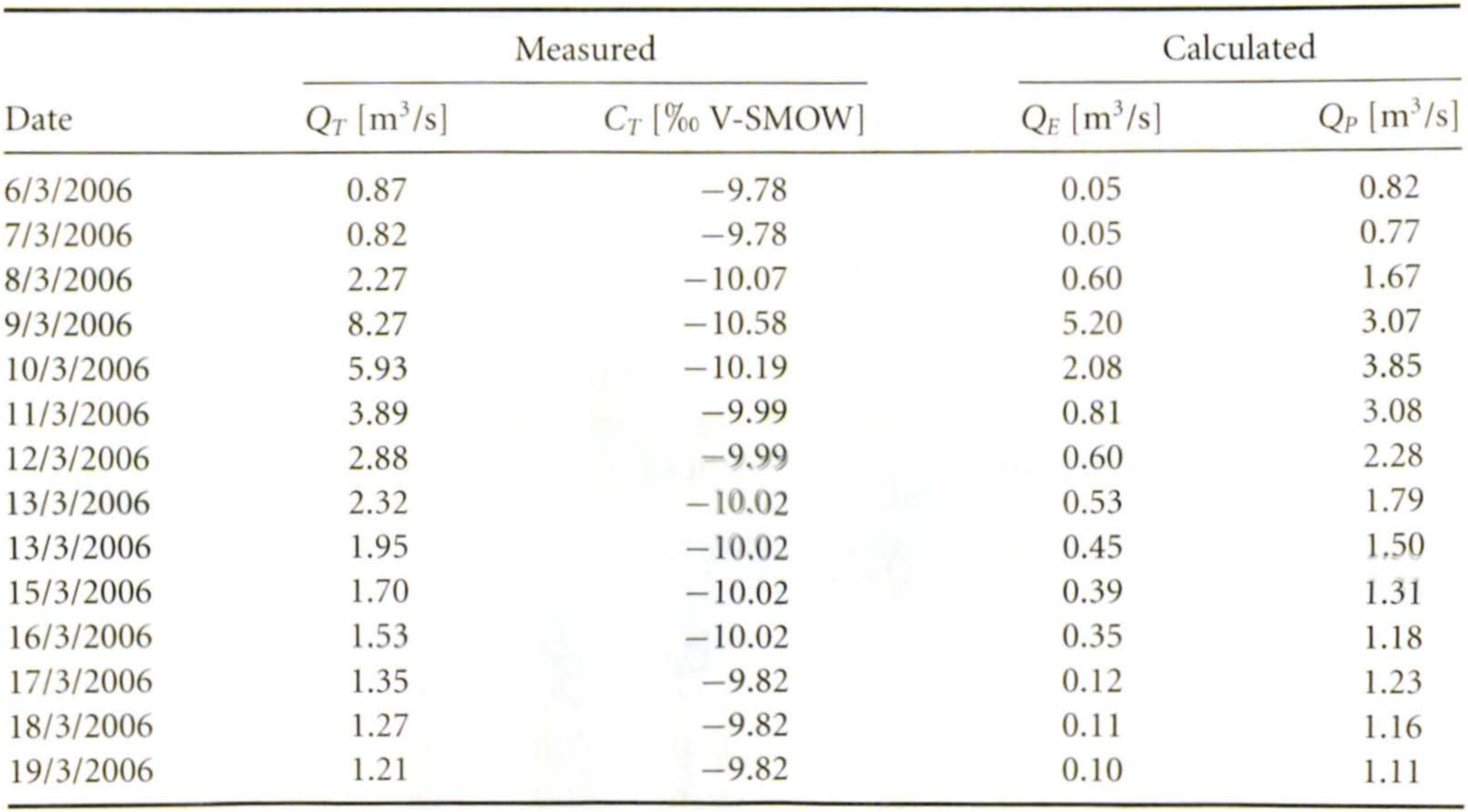


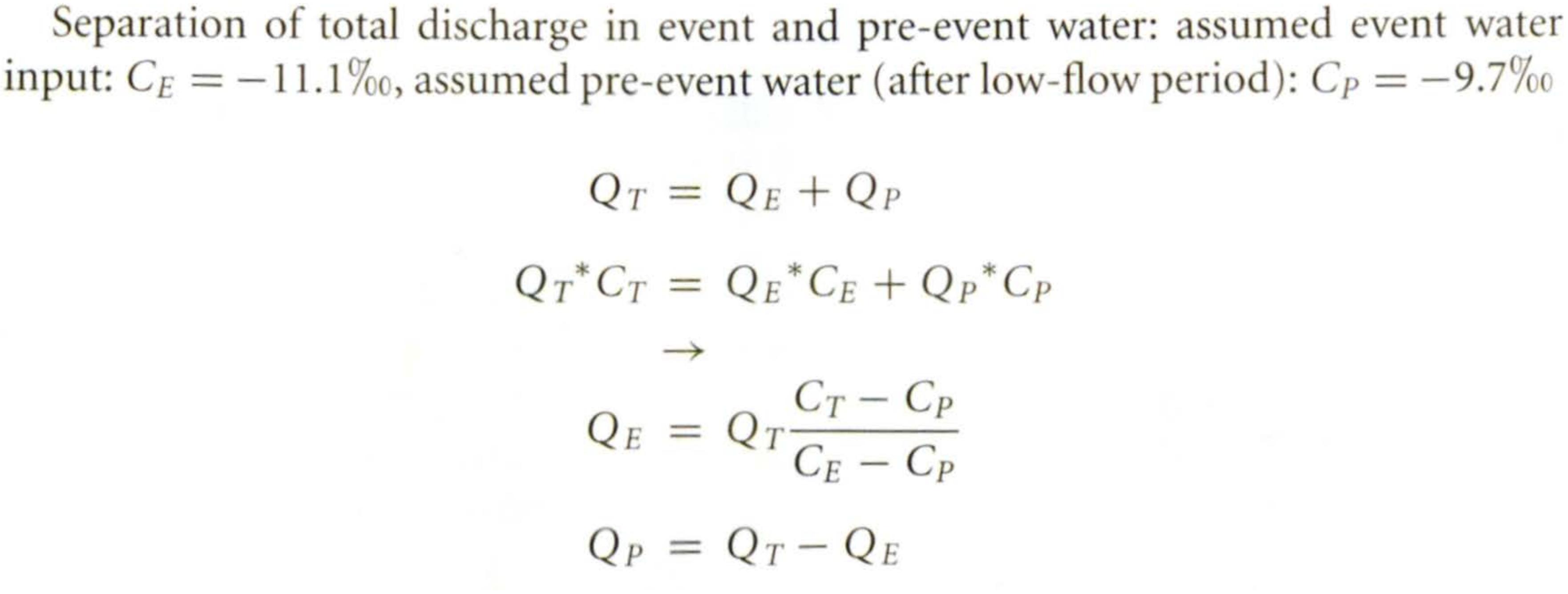
Figure Example for a hydrograph separation in event and pre-event water. Q = discharge and C = $\delta\,^{18}O$ content of E = Event water, P = Pre-event water.

Hydrograph Separation



	Measured		Calculated	
Date	Q_T [m^3/s]	C_T [‰ V-SMOW]	Q_E [m^3/s]	Q_P [m^3/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

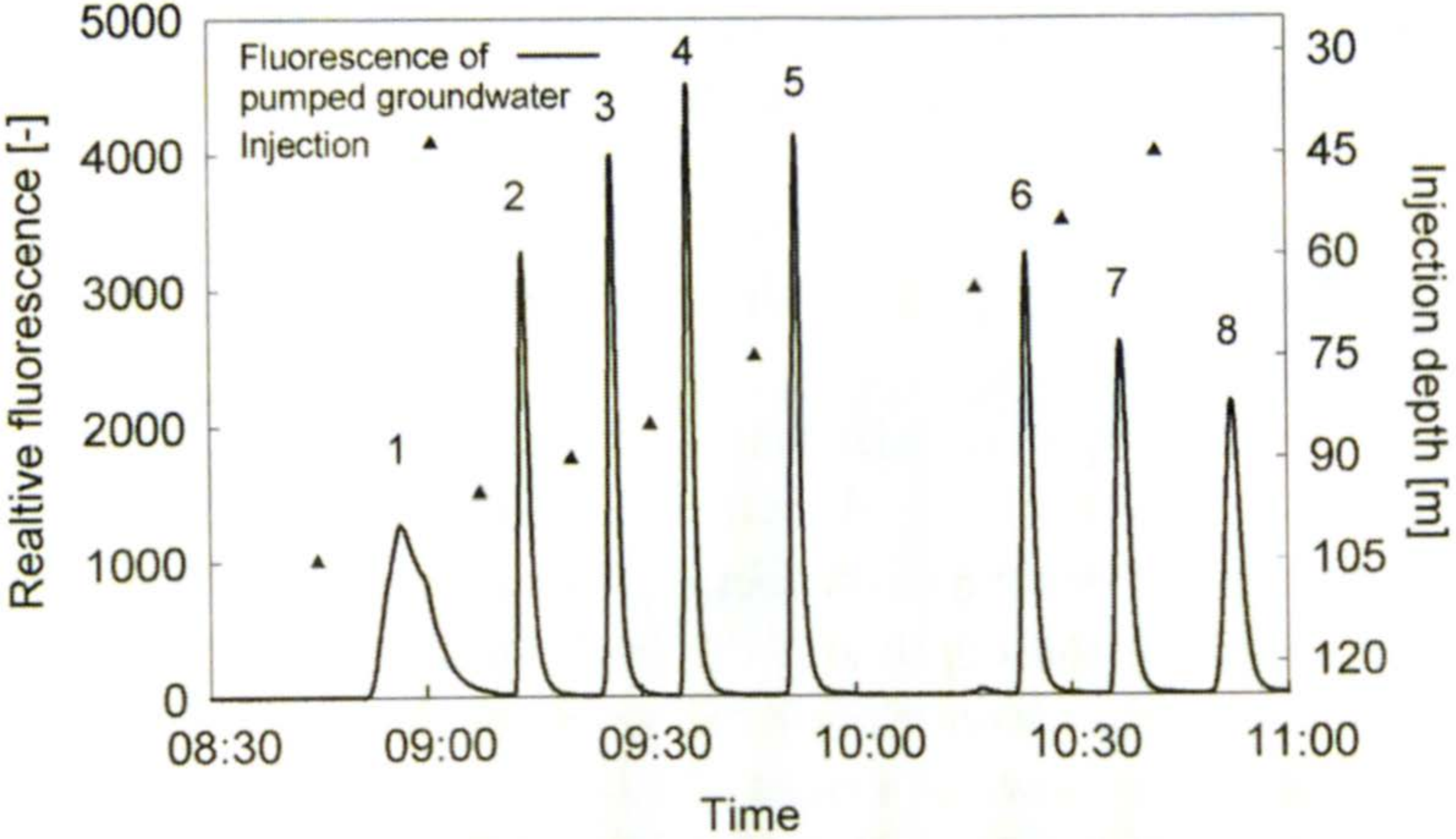
Hydrograph Separation



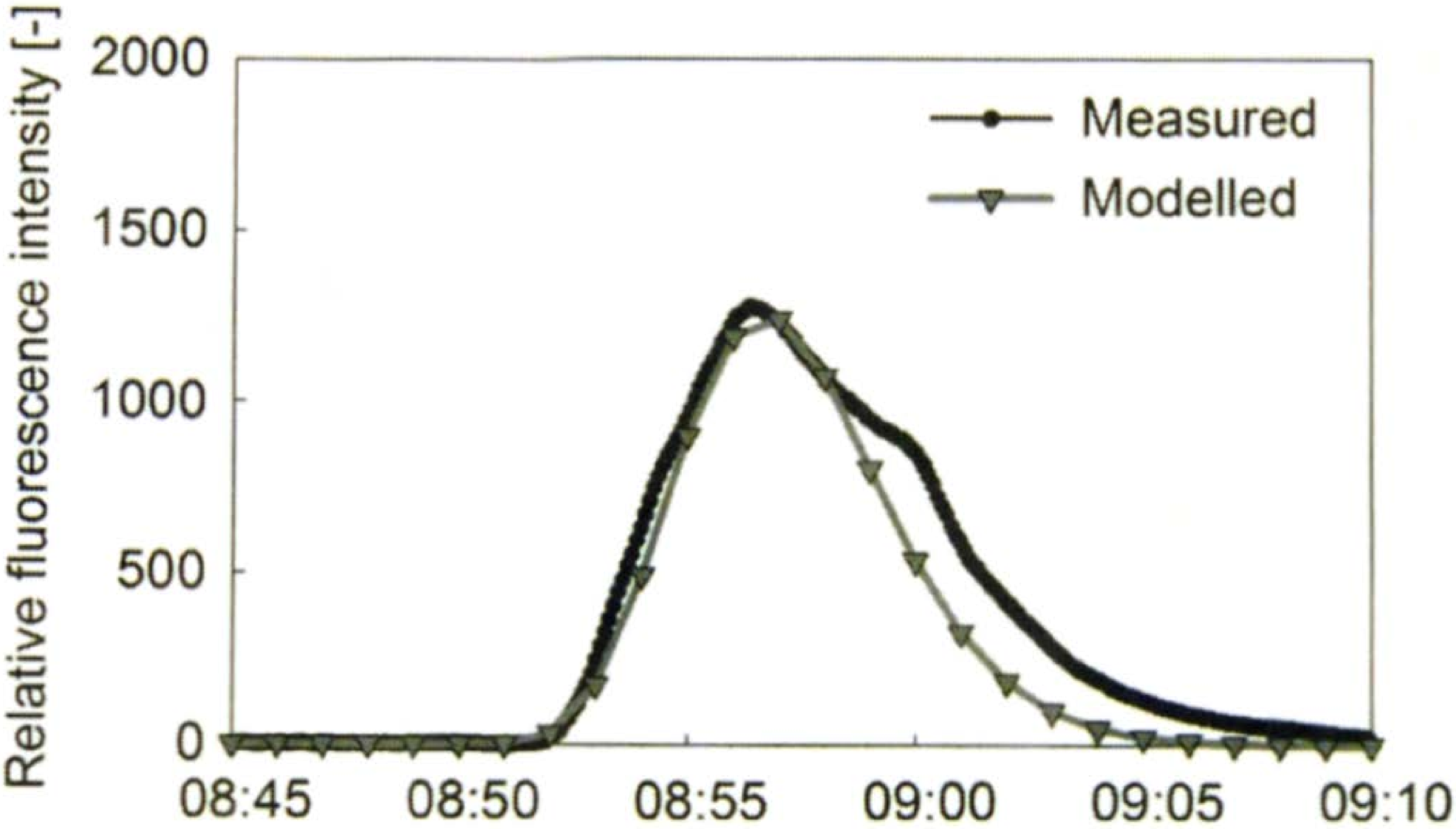
Separation of total discharge in event and pre-event water: assumed event water input: $C_E = -11.1‰$, assumed pre-event water (after low-flow period): $C_P = -9.7‰$

$$
\begin{aligned}
Q_T &= Q_E + Q_P \\
Q_T{}^* C_T &= Q_E{}^* C_E + Q_P{}^* C_P \\
&\rightarrow \\
Q_E &= Q_T \frac{C_T - C_P}{C_E - C_P} \\
Q_P &= Q_T - Q_E
\end{aligned}
$$

Single Well tests



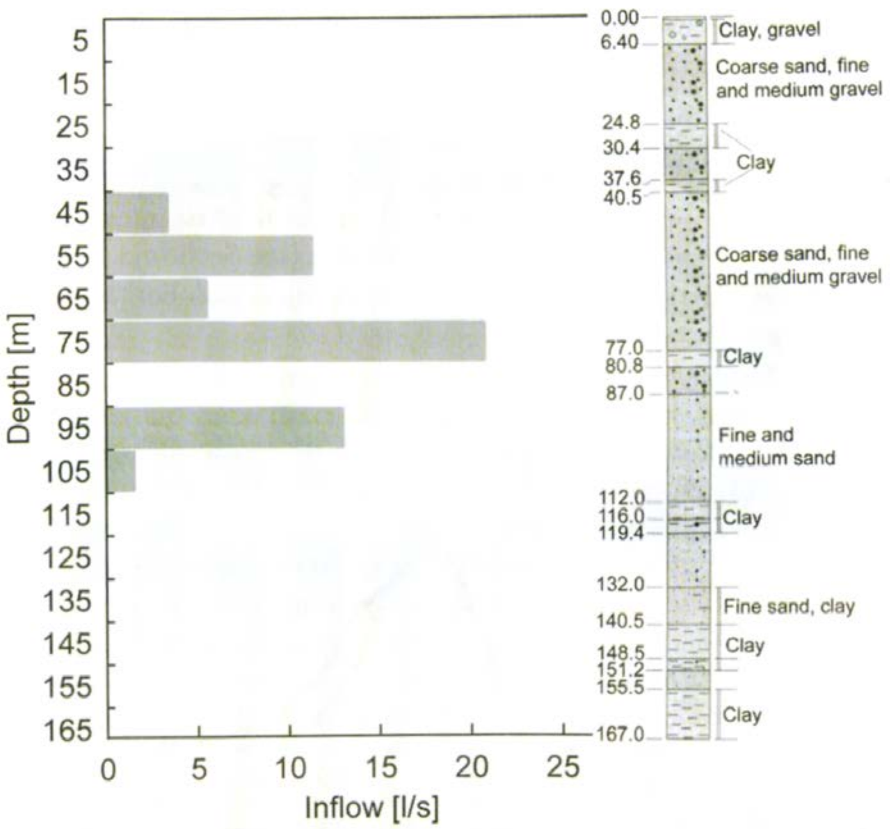
Single Well tests



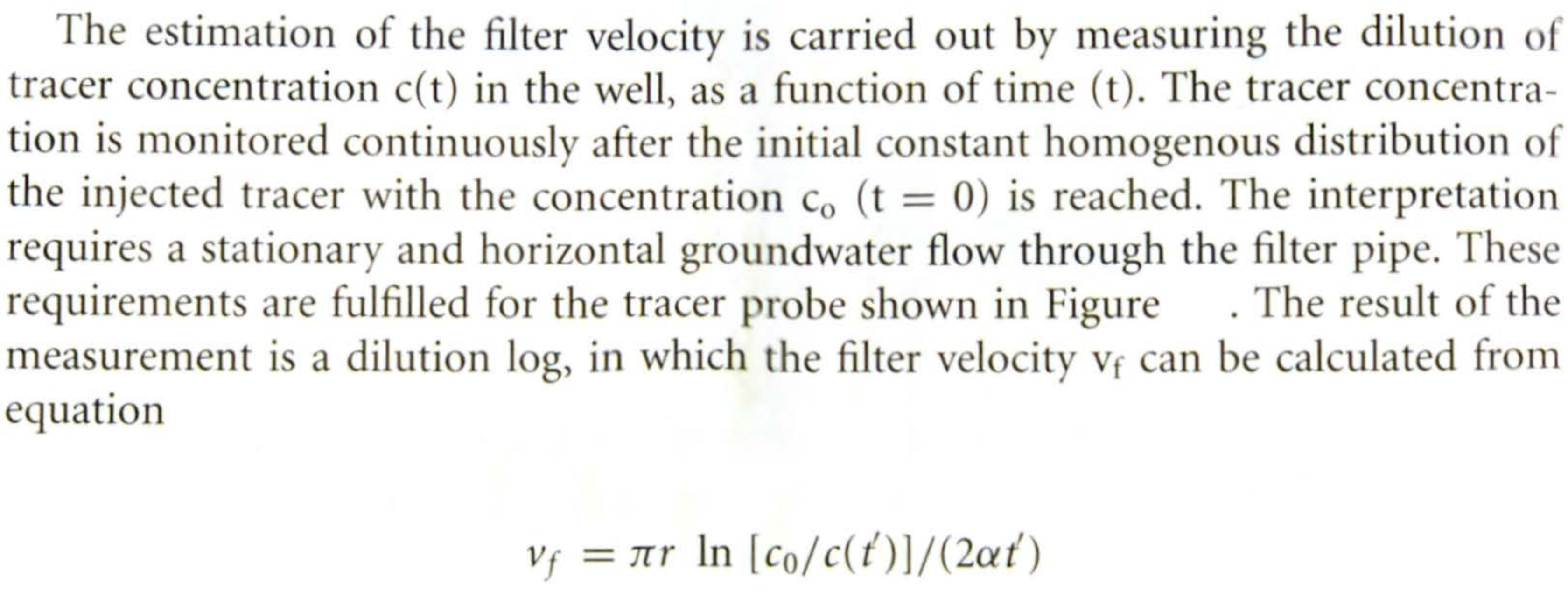
Single Well tests

From the cross-section area A of the borehole given by πr^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:

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



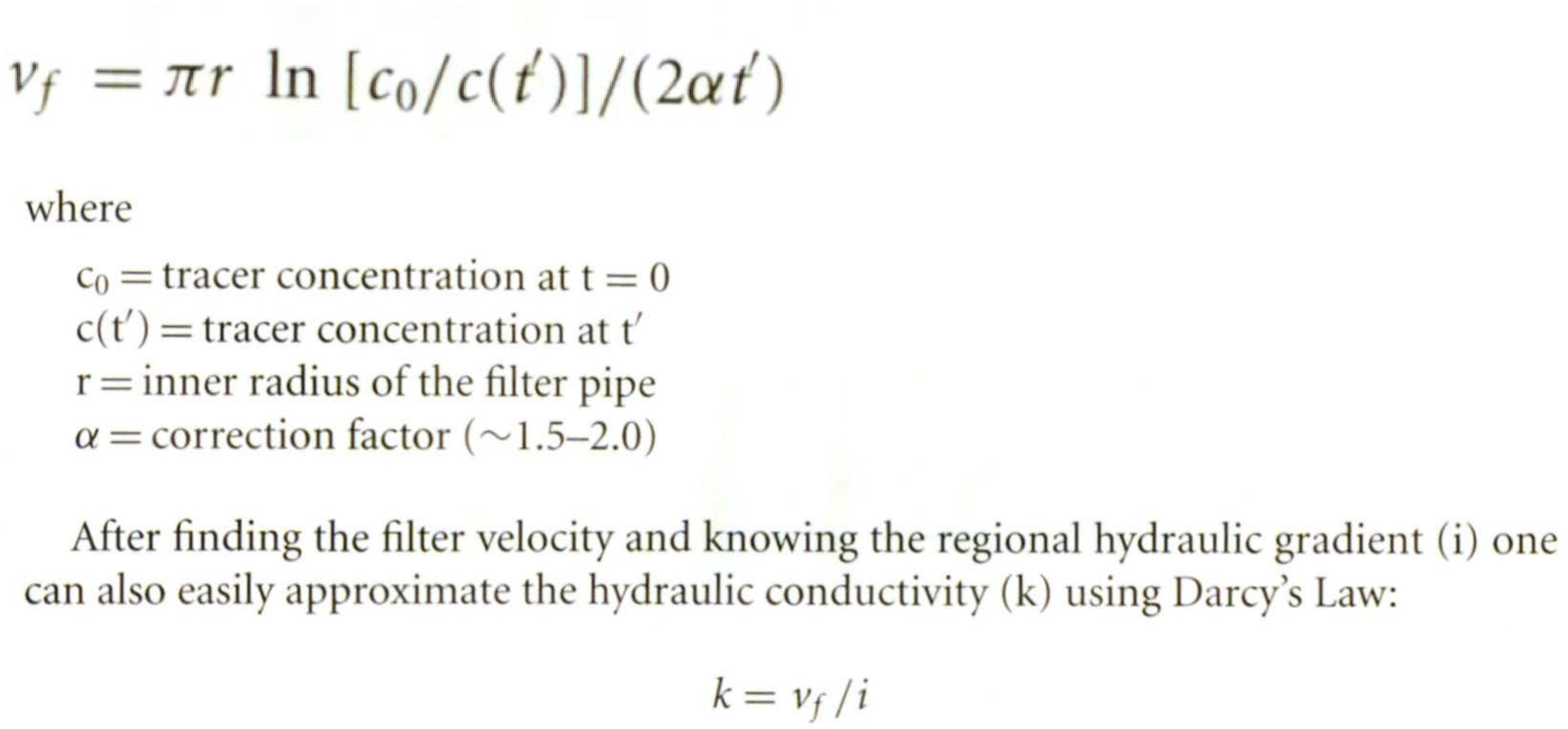
Single Well tests



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_o $(t = 0)$ 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

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

Single Well tests



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

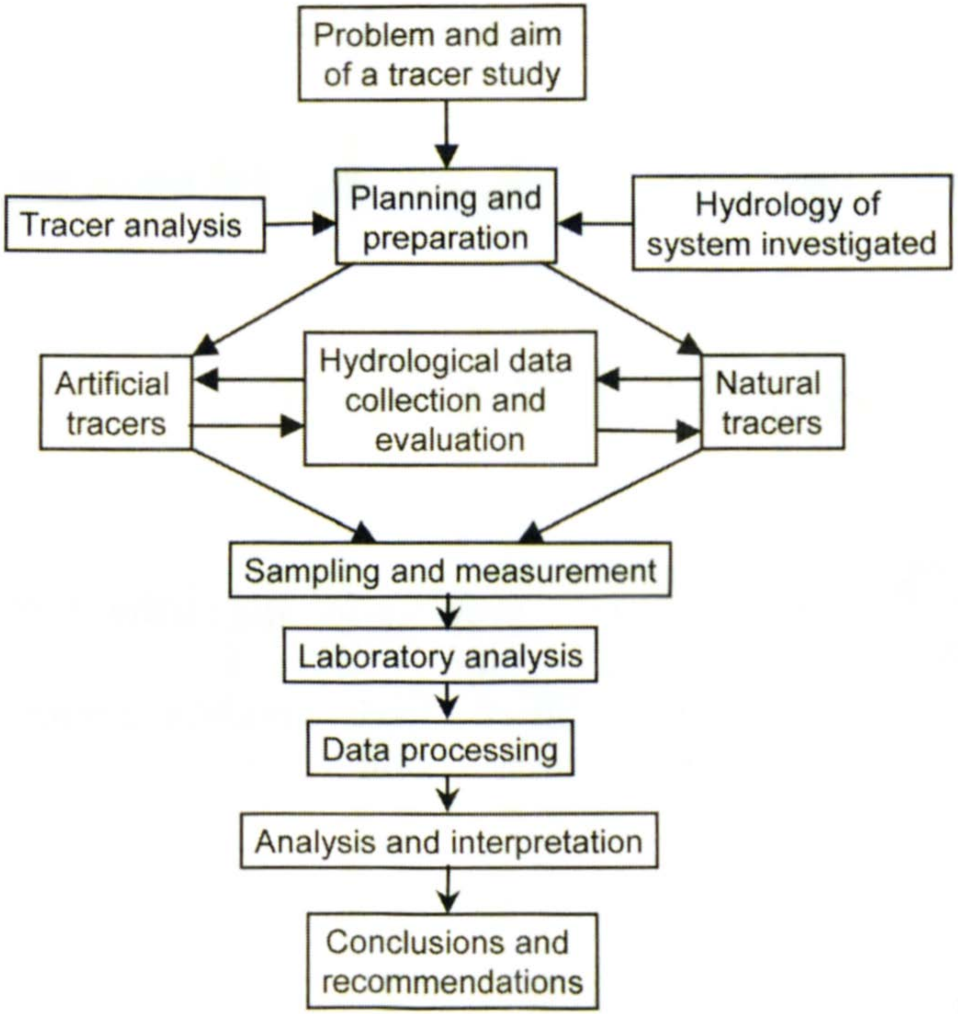
where

c_0 = tracer concentration at $t = 0$
$c(t')$ = tracer concentration at t'
r = inner radius of the filter pipe
α = correction factor (~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



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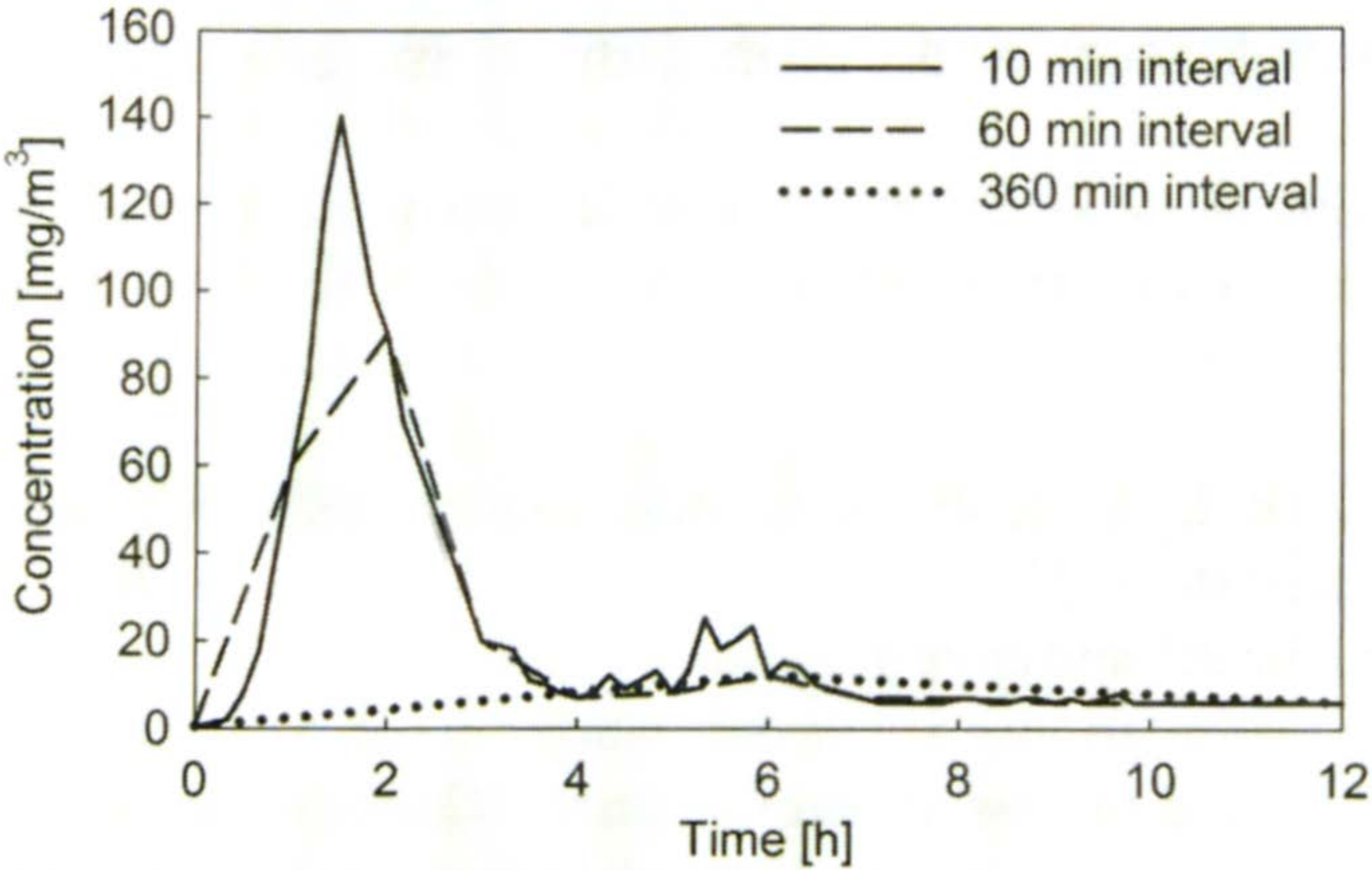

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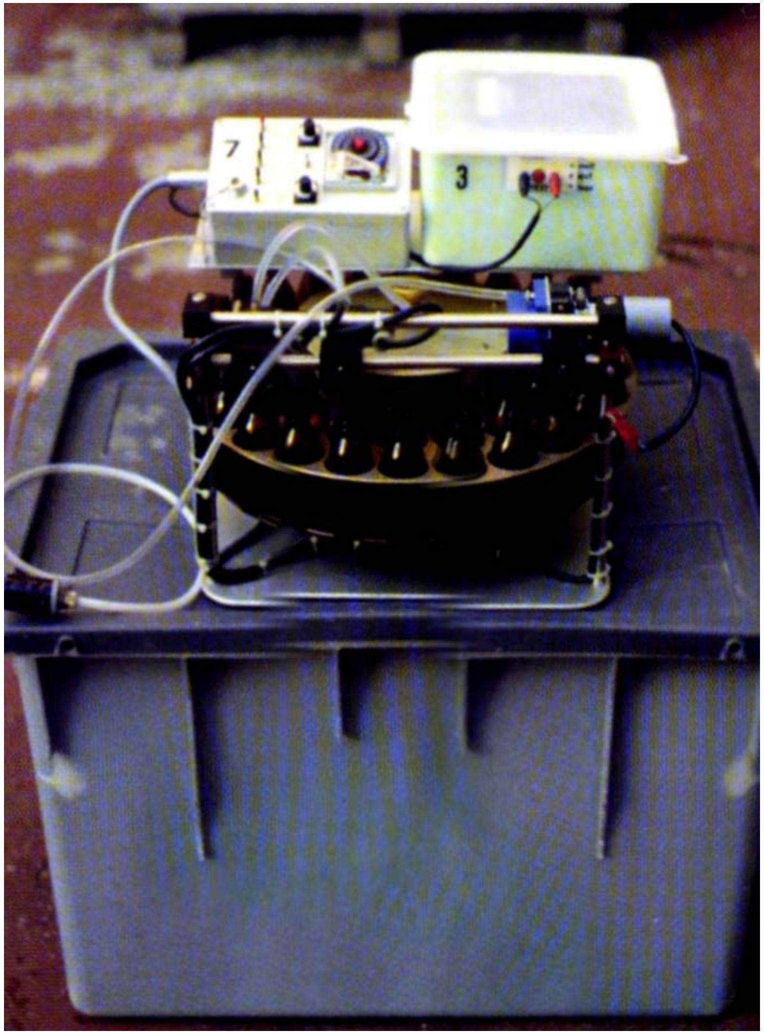

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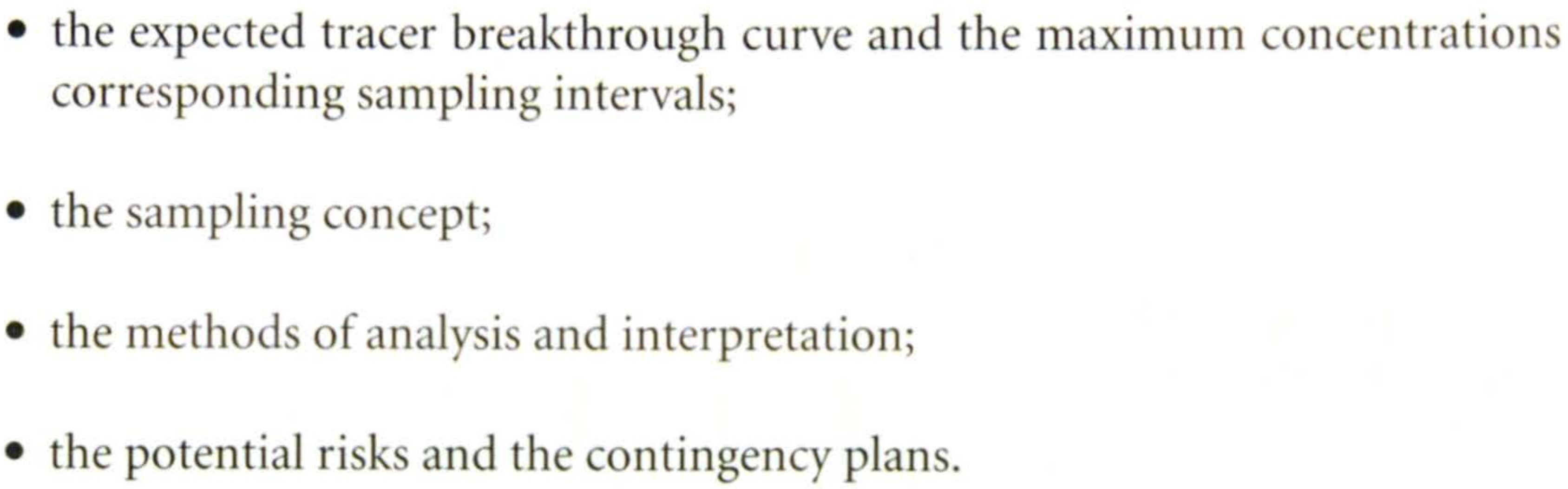
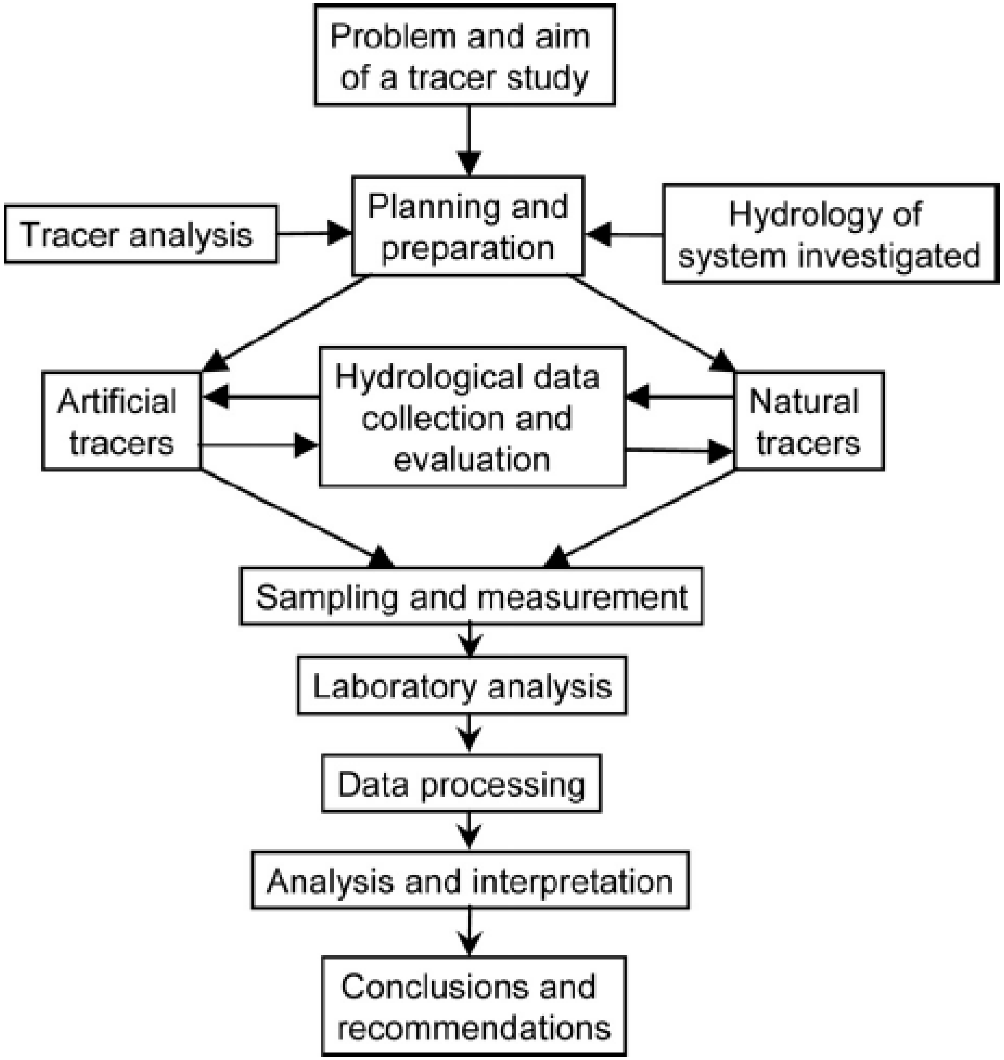
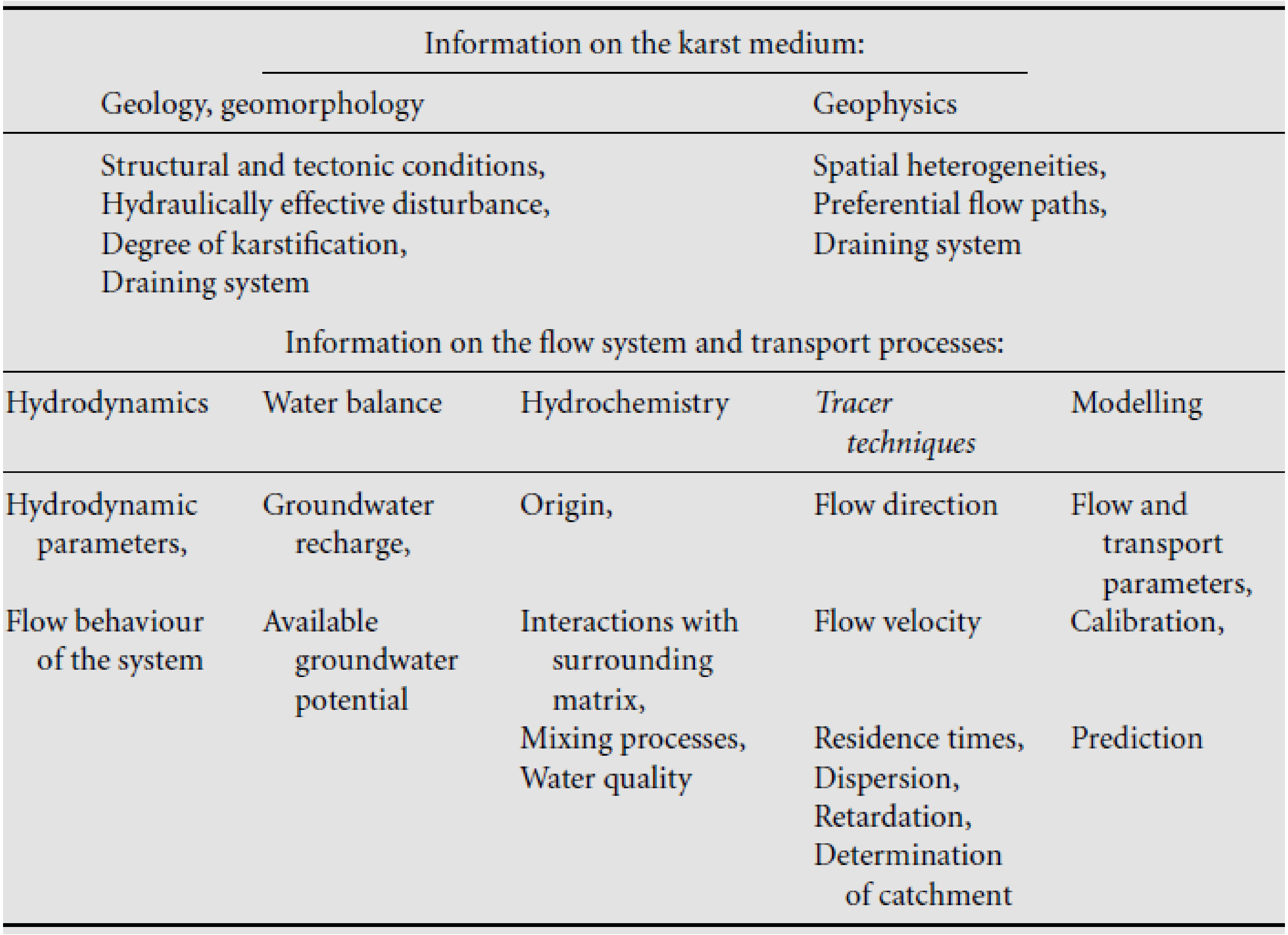


- the expected tracer breakthrough curve and the maximum concentrations corresponding sampling intervals;
- the sampling concept;
- the methods of analysis and interpretation;
- the potential risks and the contingency plans.

Planing a Tracer Test



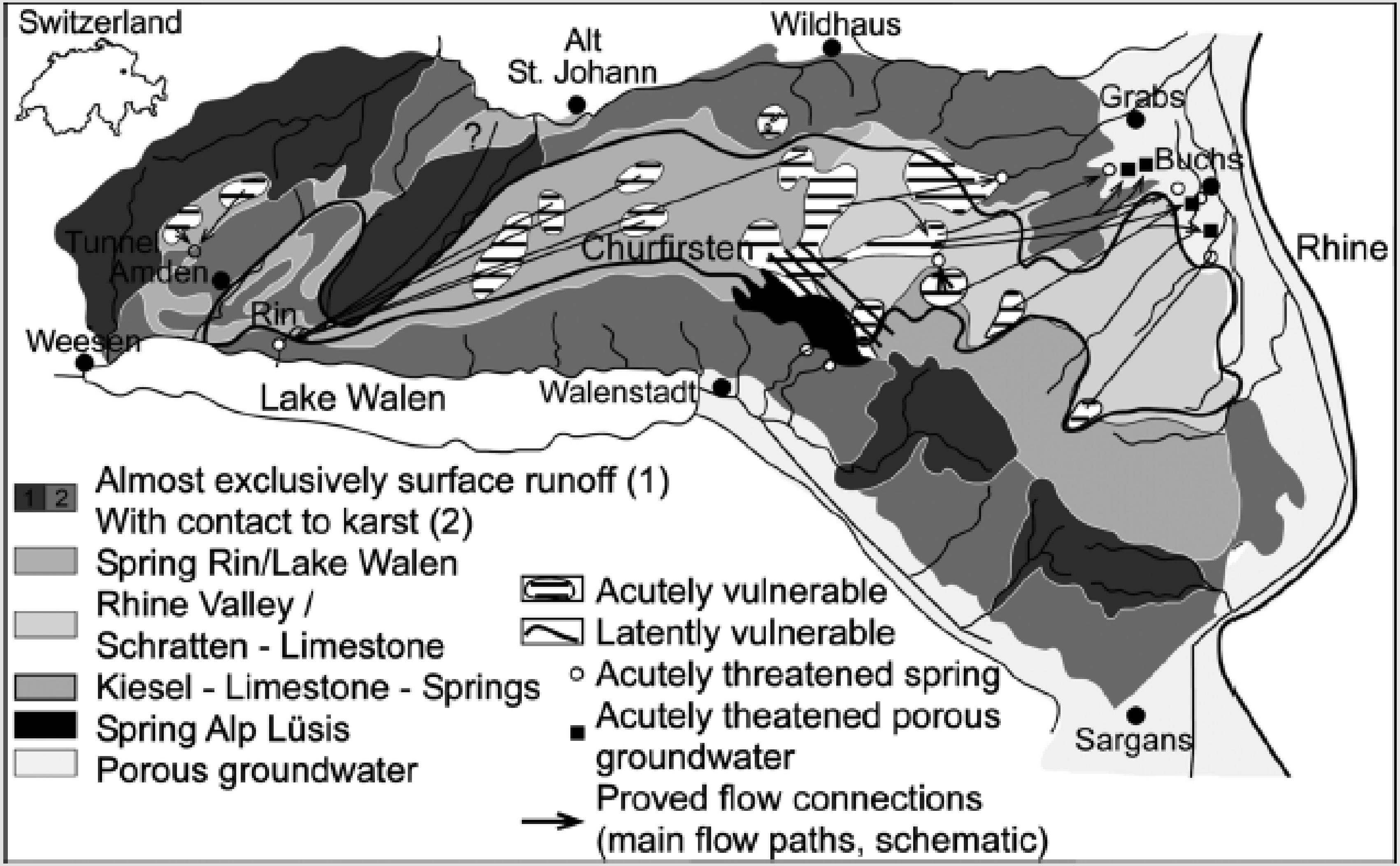
Karst studies



Information on the karst medium:	
Geology, geomorphology	Geophysics
Structural and tectonic conditions, Hydraulically effective disturbance, Degree of karstification, Draining system	Spatial heterogeneities, Preferential flow paths, Draining system

Information on the flow system and transport processes:				
Hydrodynamics	Water balance	Hydrochemistry	*Tracer techniques*	Modelling
Hydrodynamic parameters,	Groundwater recharge,	Origin,	Flow direction	Flow and transport parameters,
Flow behaviour of the system	Available groundwater potential	Interactions with surrounding matrix,	Flow velocity	Calibration,
		Mixing processes, Water quality	Residence times, Dispersion, Retardation, Determination of catchment	Prediction

Karst studies



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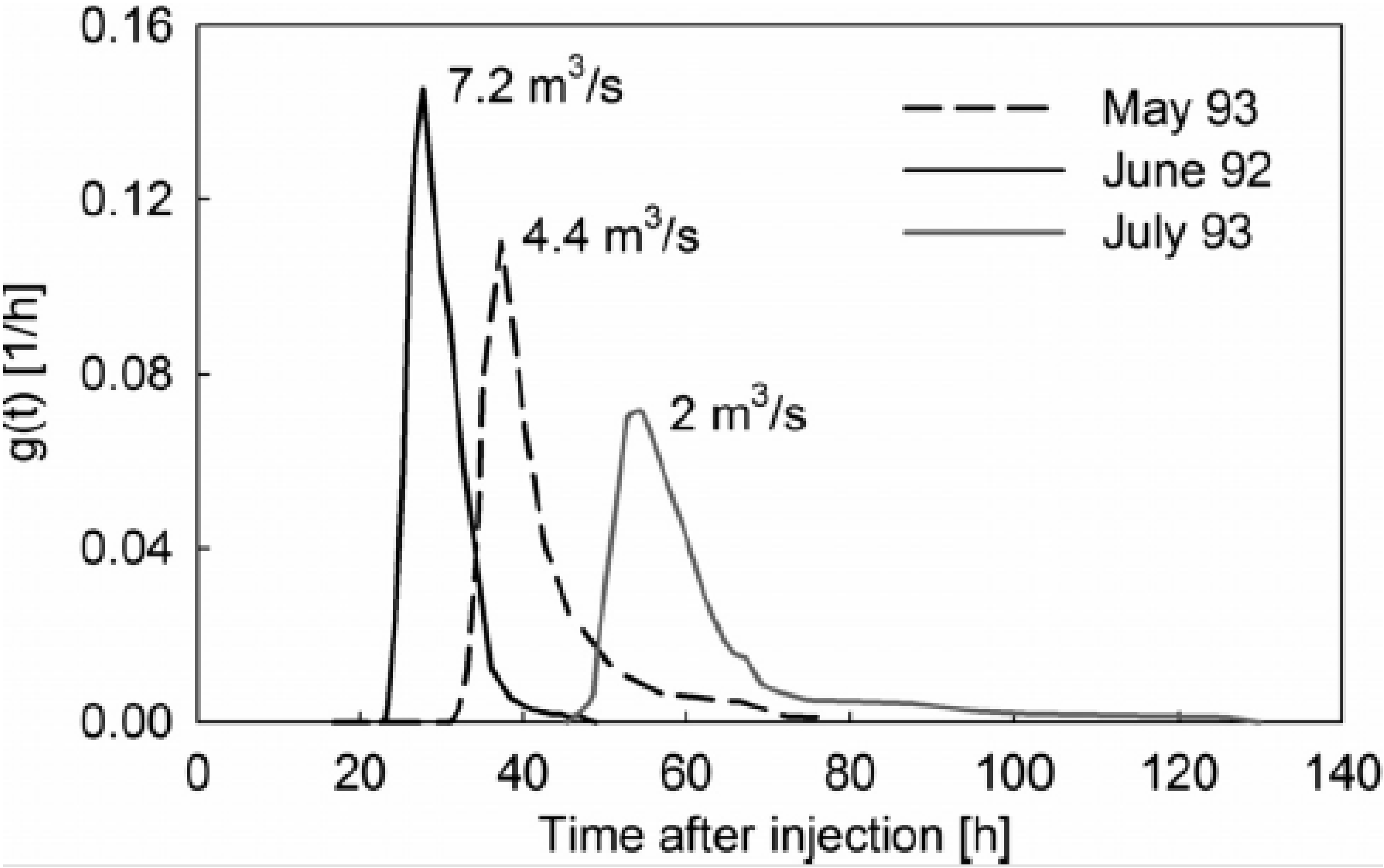
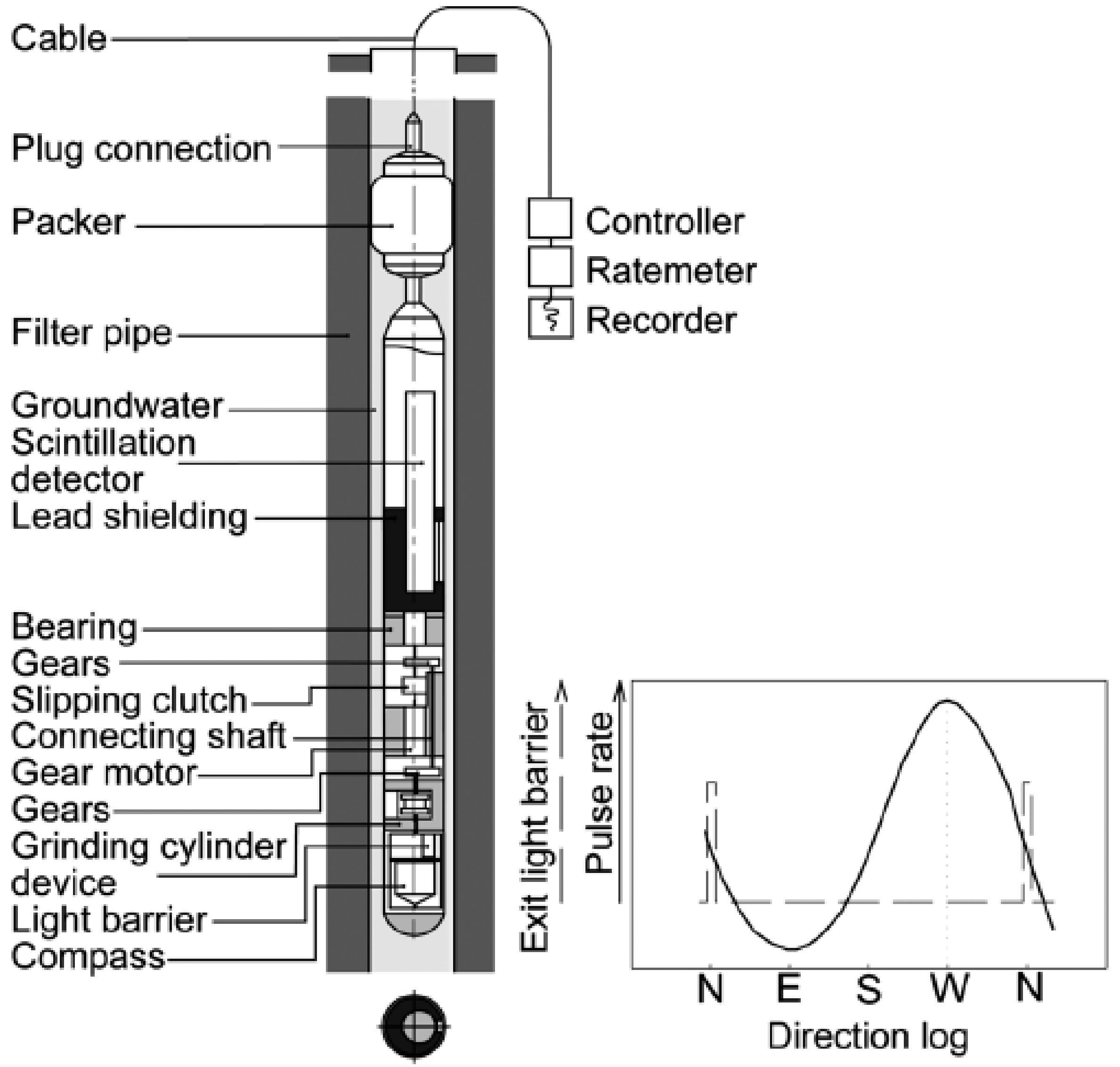


Borehole tests



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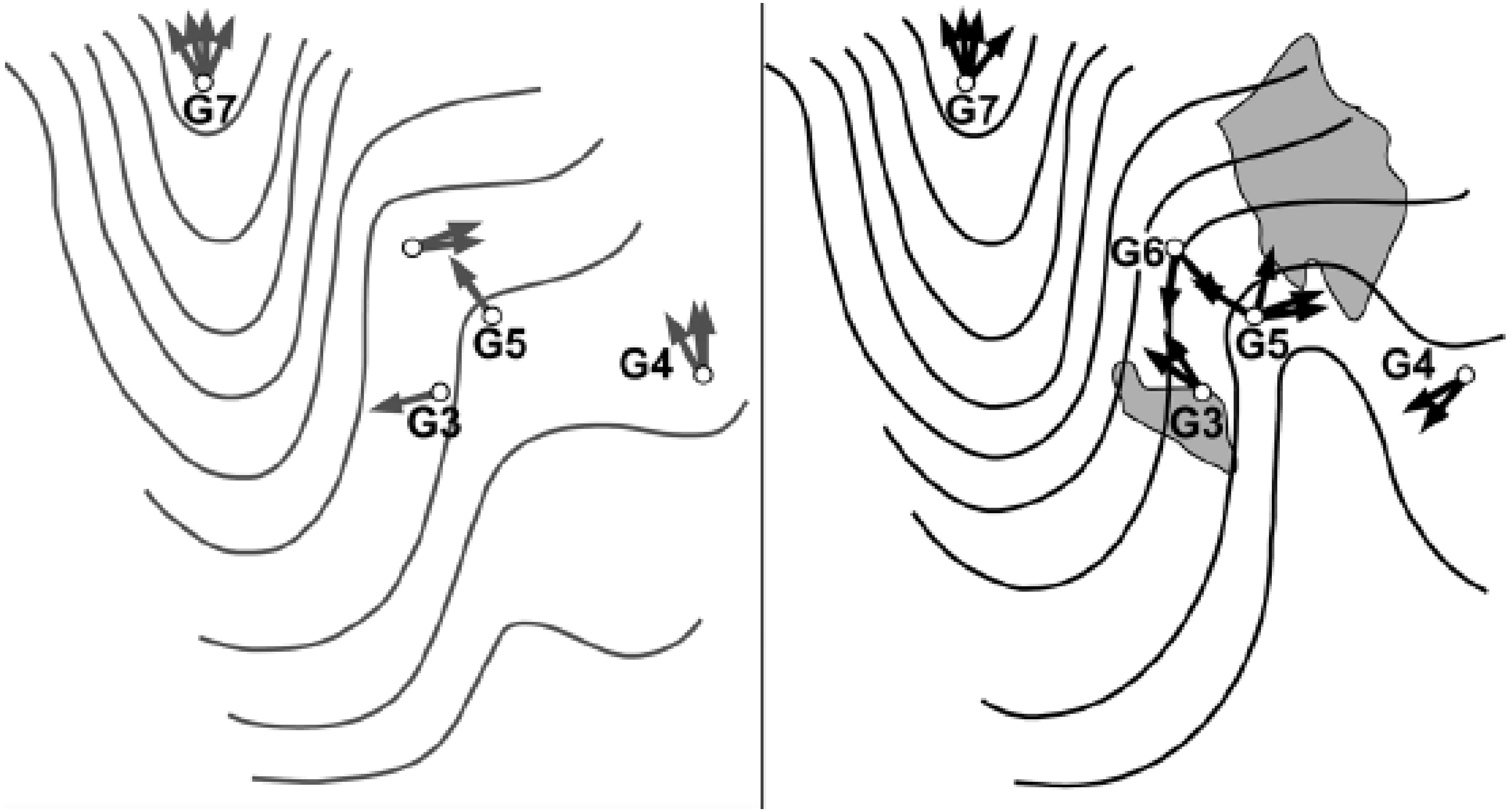
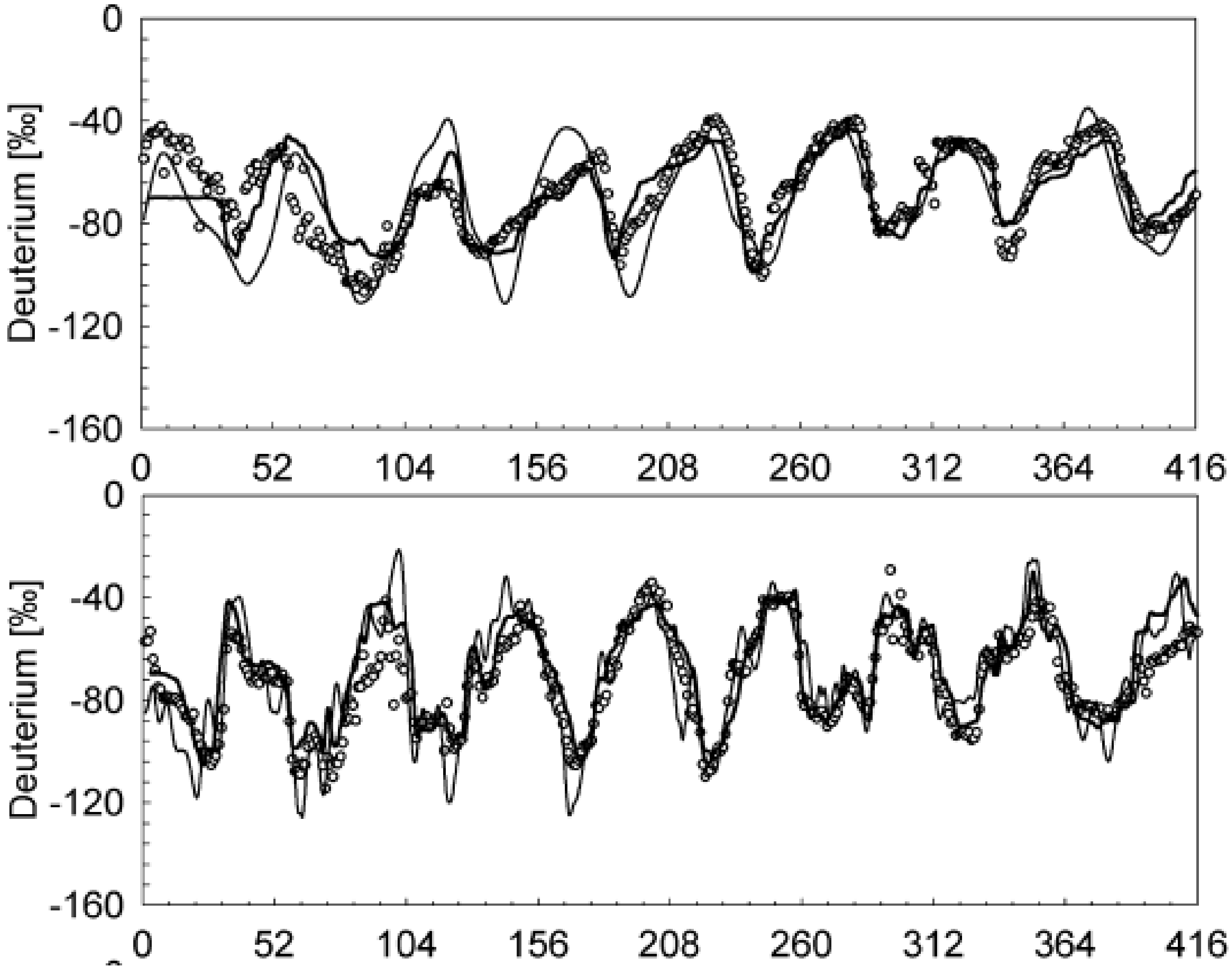
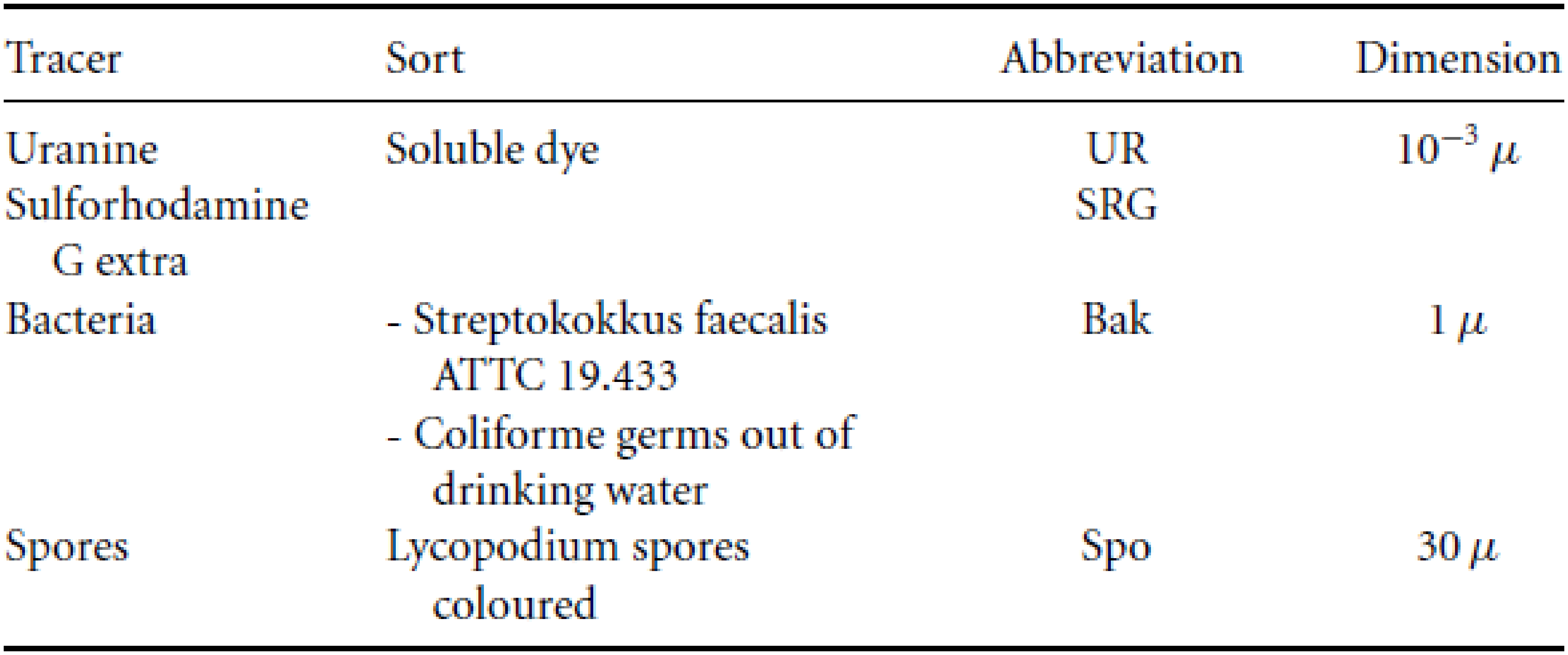


Recharge Studies in soils

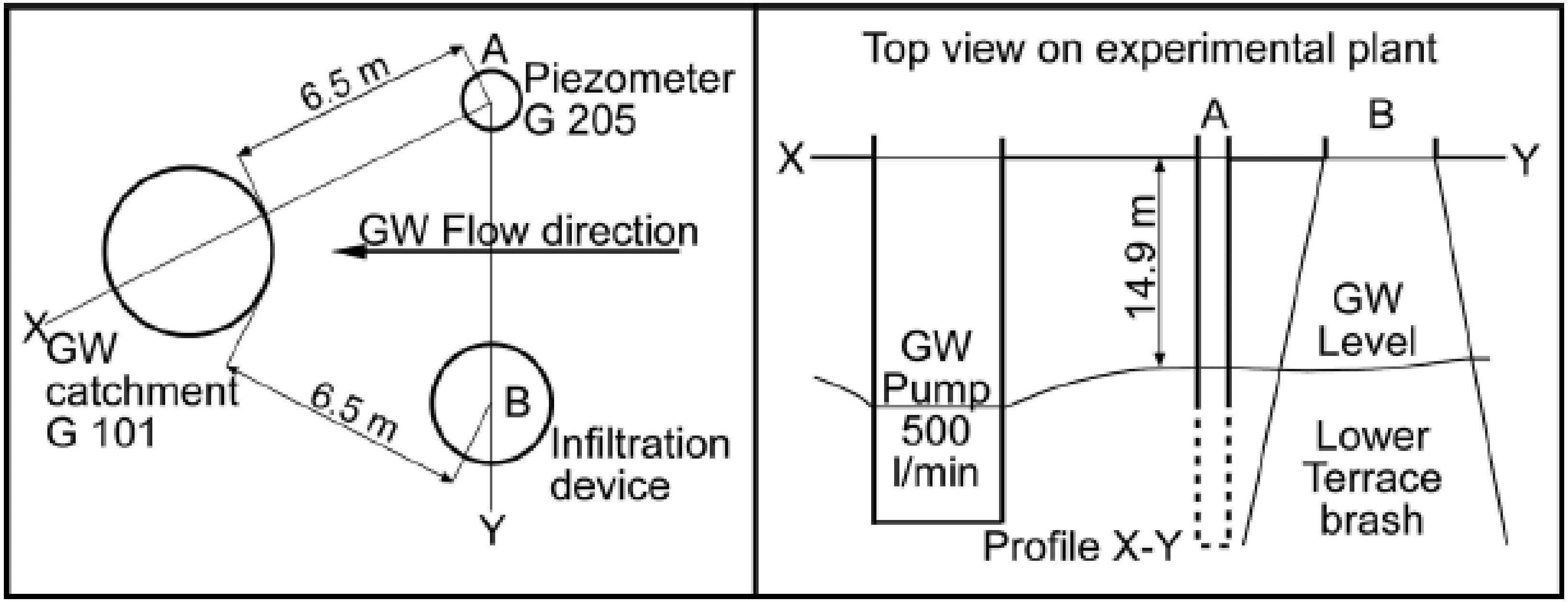


Vulnerability Studies in soils

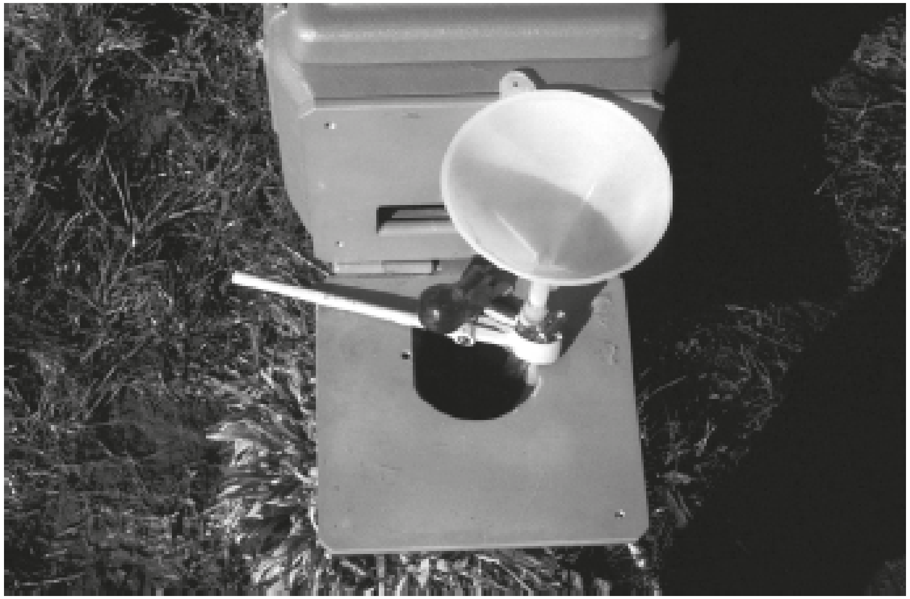


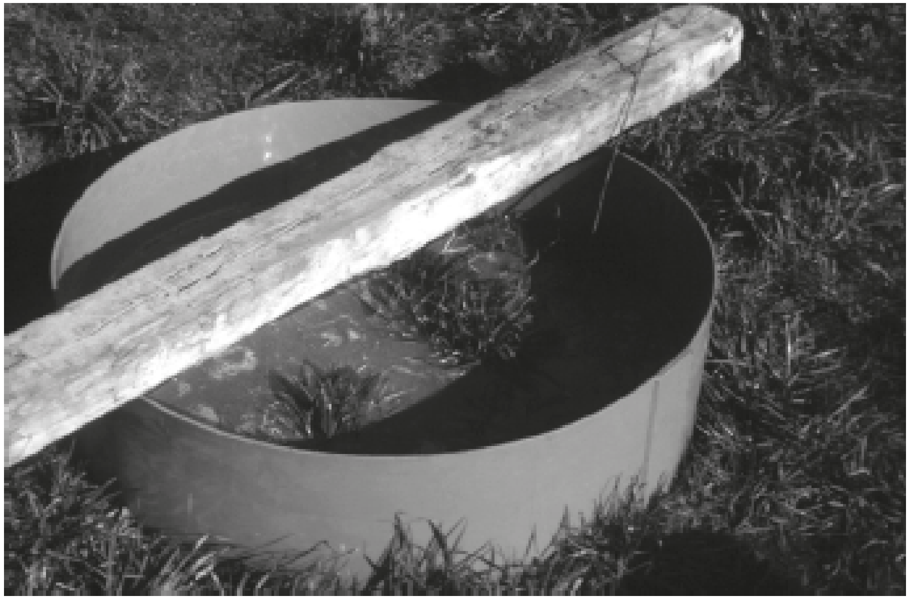
Tracer	Sort	Abbreviation	Dimension
Uranine	Soluble dye	UR	$10^{-3}\ \mu$
Sulforhodamine G extra		SRG	
Bacteria	- Streptokokkus faecalis ATTC 19.433 - Coliforme germs out of drinking water	Bak	$1\ \mu$
Spores	Lycopodium spores coloured	Spo	$30\ \mu$

Vulnerability Studies in soils

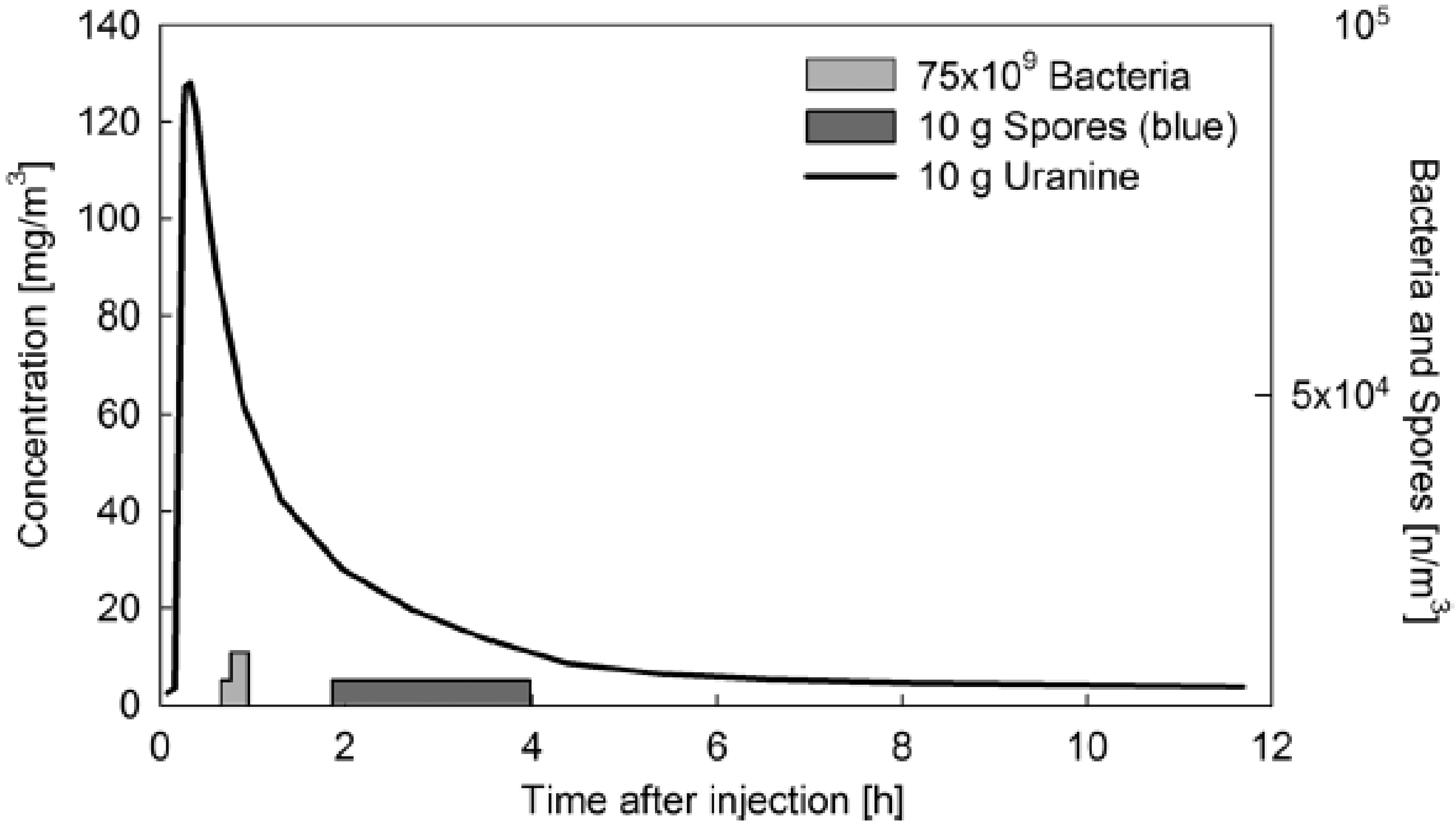


Vulnerability Studies in soils





Vulnerability Studies in soils



Vulnerability Studies in soils

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