Karlsruhe Institute of Technology

Tracer tests and water quality monitoring for karst groundwater protection and management

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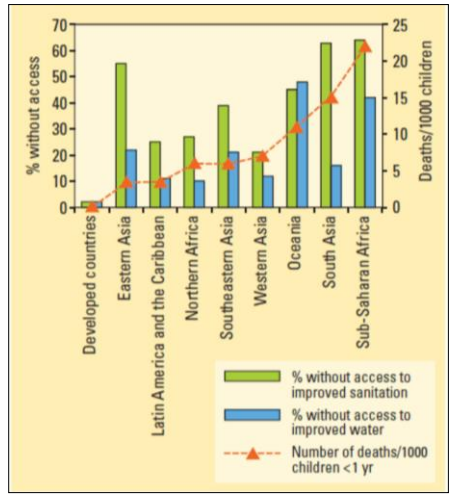
Major Challenge for Humanity: Safe Drinking Water

Direct relation between lack of access to improved water sources and deaths attributable to diarrheal diseases.

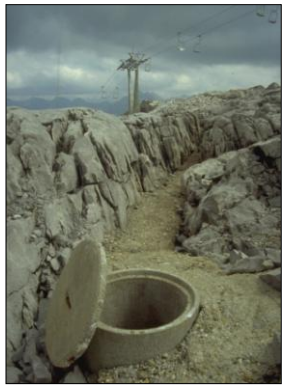


Children in a Vietnamese karst area

WHO

Global importance of karst groundwater

- Ca. 25 % of the global population are supplied by drinking water from karst aquifers (Ford & Williams 1989, 2007).
- At the same time, karst aquifers are highly vulnerable to contamination, including microbial contamination.



Wastewater injection into an alpine karst aquifer

Drinking water drainage gallery in an alpine karst aquifer

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all photos and figures without other reference: Nico Goldscheider

Large areas without surface drainage

Karst area “Hochifen-Gottesacker”, Bavarian-Austrian Alps

- Rapid infiltration through thin soils and into solutionally enlarged fractures of the epikarst zone.

➔ Little protection against contamination = high vulnerability

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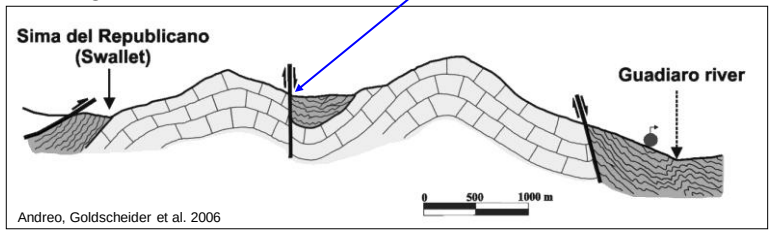
Surface streams sinking into swallow holes

Example: swallow hole in the Sierra de Líbar, Spain

Geologic situation:



Andreo, Goldscheider et al. 2006

➔ Contaminants can directly enter the groundwater, without filtration, often together with suspended particles (turbidity).

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Rapid and often turbulent flow in a network of fractures, conduits and caves...

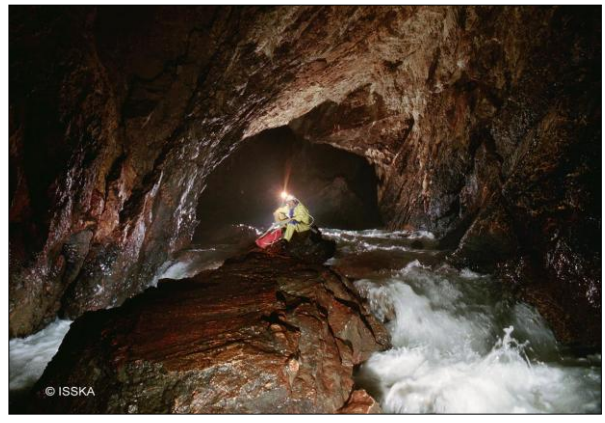
Reynolds number, R [-]

$$R = \frac{\rho \cdot v \cdot d}{\mu}$$

ρ: fluid density
v : flow velocity
d: pipe diameter
μ: viscosity

[kg, m, s]

R < 500 : laminar
500-2000 : transitional
R > 2000 : turbulent



Water cave in the Swiss Jura Mountains (photo: R. Wenger)

➔ Rapid transport of sediment particles and associated contaminants

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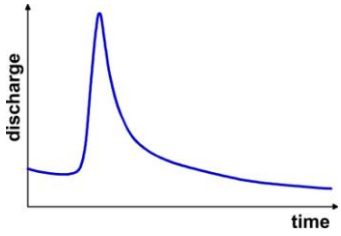
… towards large springs, often characterised by rapid and marked discharge variations

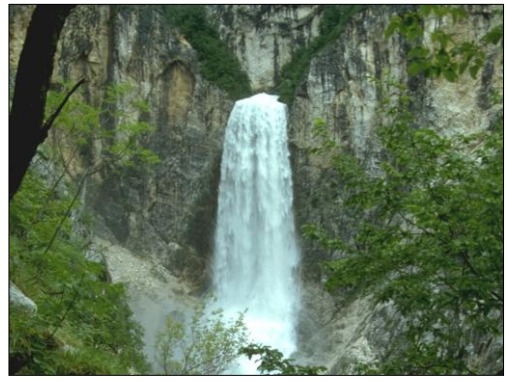


Hydrograph formula:

$$Q = Q_{max}\left(\frac{2eb}{3t}\right)^{3/2} e^{-b/t}$$

Q = discharge
e = Euler's number
b = time constant
t = time

Criss & Winston 2003



Boka Spring, Slovenia

➔ Important freshwater sources, but difficult to manage

Large fluctuations of the water table and associated surface waters, sometimes > 100 m

Intermittent lake in Slovenia, which fills and empties via numerous fractures and a cave that can act as springs or swallow holes

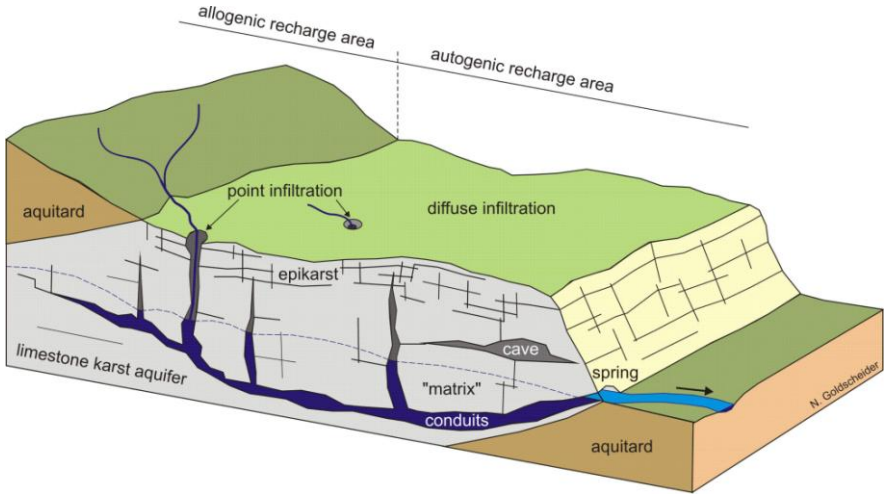
karst depression, dry

karst depression, flooded

➔ "Flooding problem" or "Groundwater-Dependent Ecosystem"

photos: Nataša Ravbar

Hydrogeological Structure of Karst Systems



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Goldscheider & Drew, 2007, modified

“Duality” of conduits and rock matrix in nature

Spring emerging from an open cave, *Cirque de Consolation*, French Jura Mountains

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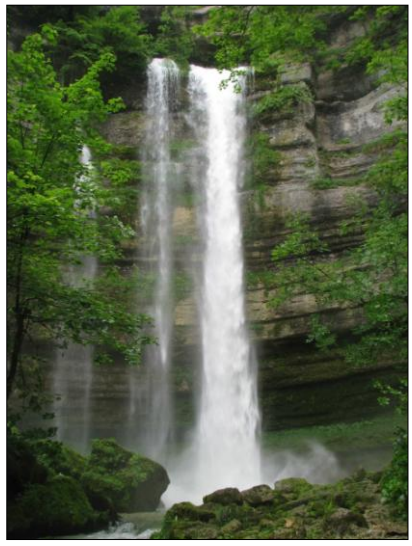
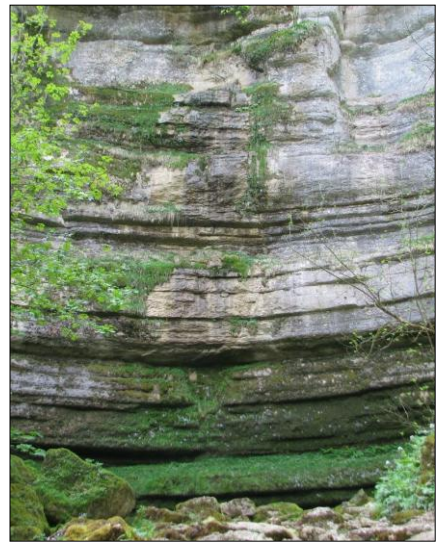
Photos without other reference: Nico Goldscheider

Same spring from another perspective: flow variability



8 June 2006: high-flow conditions



8 May 2009: spring dry

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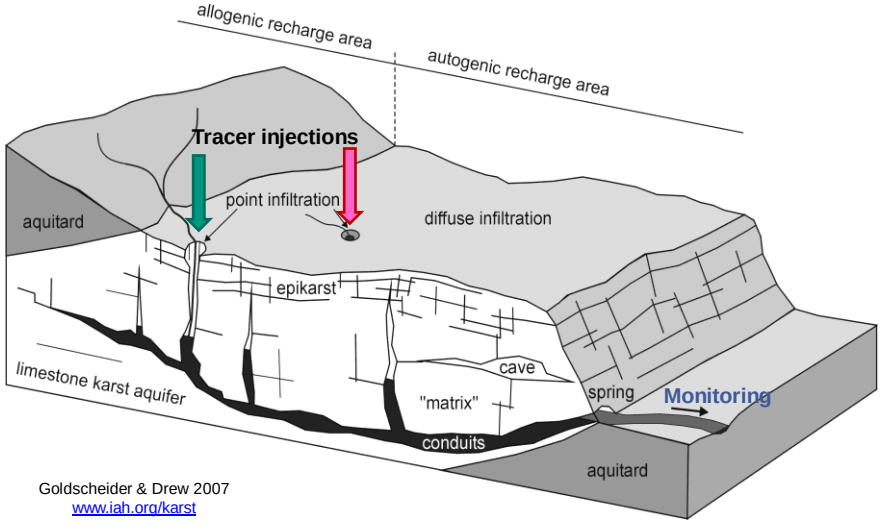
Principle of a tracer test in a karst aquifer



Goldscheider & Drew 2007
www.iah.org/karst

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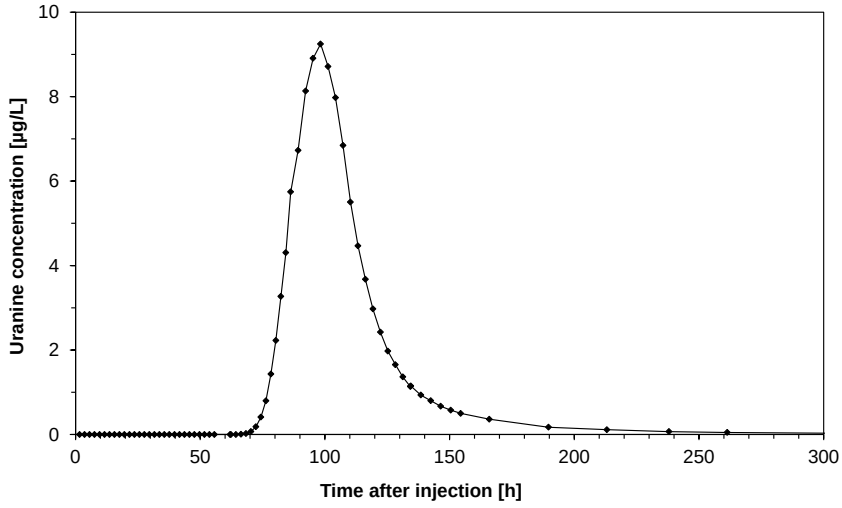
Primary result of a tracer test: Breakthrough Curve



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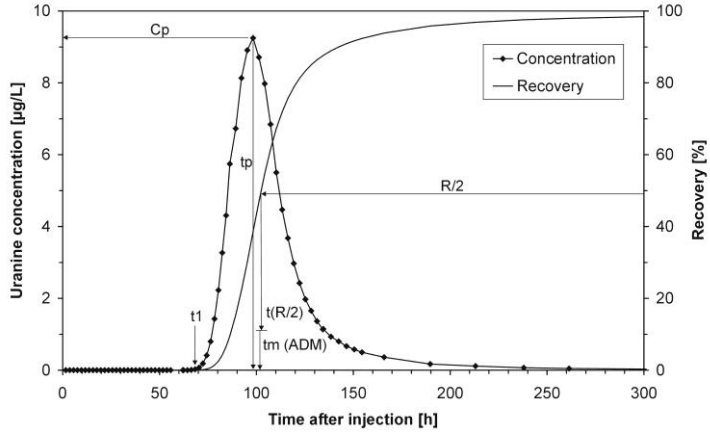
Goldscheider et al. (2008)

Evaluation of a Tracer Breakthrough Curve



t1 = time of first tracer detection
tp = peak time, Cp = peak (or maximum) concentration
t(R/2) = time when half of the recovered tracer has passed the sampling site
tm (ADM) = mean transit time (obtained from Advection-Dispersion Model)

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Goldscheider et al. (2008)

Calculation of the tracer recovery

Constant flow rate

$$R_M = Q \int_{t=0}^{\infty} c\, dt$$

variable flow rate

$$R_M = \int_{0}^{\infty} cQdt$$

R_M : recovered tracer mass
Q : discharge/pump rate
c : tracer concentration

Result can be expressed as absolute quantity (g, kg) or relative quantity (%)

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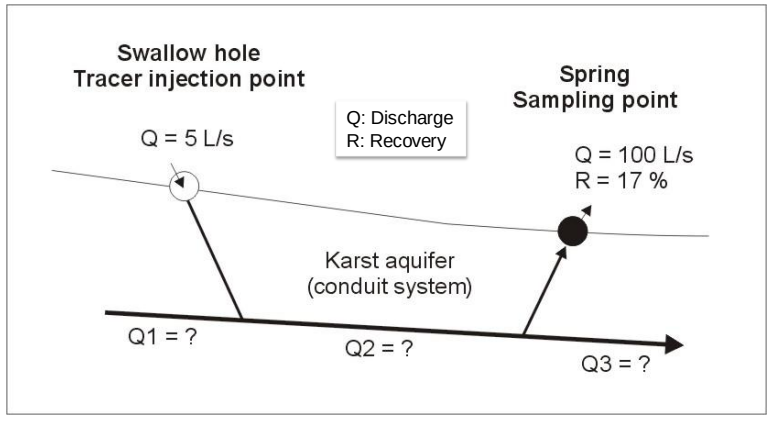
Exercise: Calculation of underground flow rates



Calculate the flow rates inside the karst conduit system!
Assumptions: ideally conservative tracer and ideal experimental conditions

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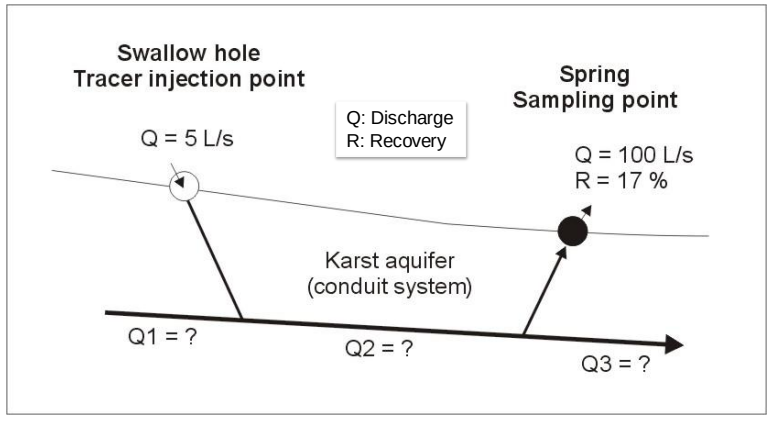
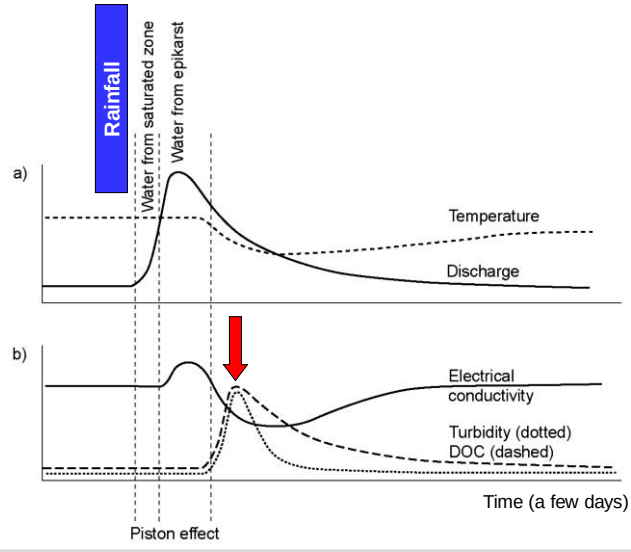
Solution: simple rule of three



$$\frac{Q3}{Q(spring)} = \frac{100-R}{R} \qquad \frac{Q3}{Q(spring)} = 100 L/s \frac{83}{17}$$

Q3 = 488 L/s
Q2 = 588 L/s
Q1 = 583 L/s

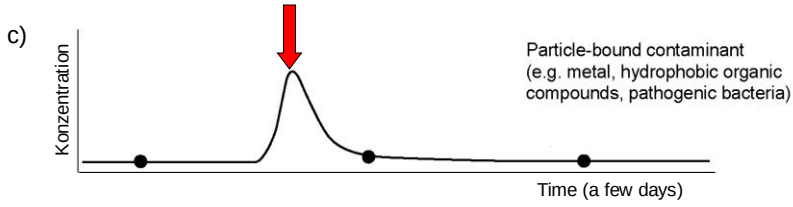
Variability of discharge and physicochemical parameters at a karst spring



Hunkeler & Mudry, in Goldscheider & Drew (2007)

... and the consequences for monitoring and detection of karst spring water contamination

- Contaminant concentrations are often even more variable than discharge and physicochemical parameters.
- Regular sampling intervals (e.g. weekly, monthly) are very likely to miss the contamination event.
- Continuous online monitoring is always preferred.



19 Hunkeler & Mudry, in Goldscheider & Drew (2007)

Problem: fecal bacteria and microbial pathogens cannot be measured continuously and online

- We need an “early-warning system” for microbial contamination.
- Parameter or combination of parameters that can be monitored continuously and that indicates the possible presence of pathogens.
- Starting point for a research project (2004-2008, Swiss National Science Foundation). Test site: City of Yverdon, Switzerland.

The main drinking water supply spring of Yverdon, Switzerland

20 Photo: Goldscheider

Case Study from Yverdon, Switzerland

Goal: Identify Early-Warning Parameters for Microbial Contamination of Drinking Water from Karst Springs

Photo: Goldscheider

Swallow hole where frequently contaminated surface water from agricultural land sinks underground into the karst aquifer

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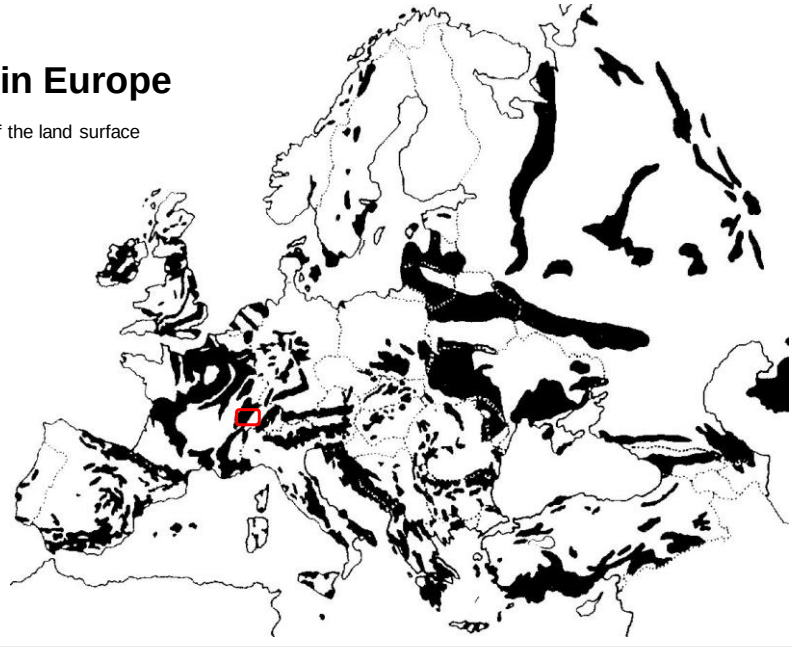
Karst in Europe

35 % of the land surface



COST 65, 1995

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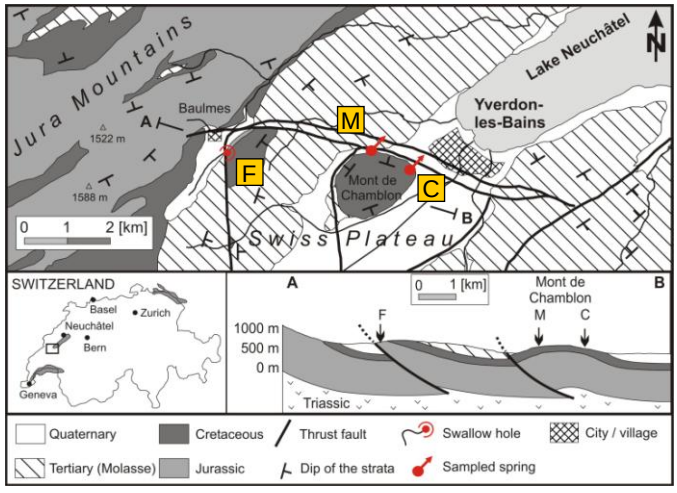
Karst system near Yverdon: Hydrogeology



Pronk, Goldscheider & Zopfi, 2006, 2007 and 2009

F Feurtille swallow hole

Q = 0 - 500 L/s

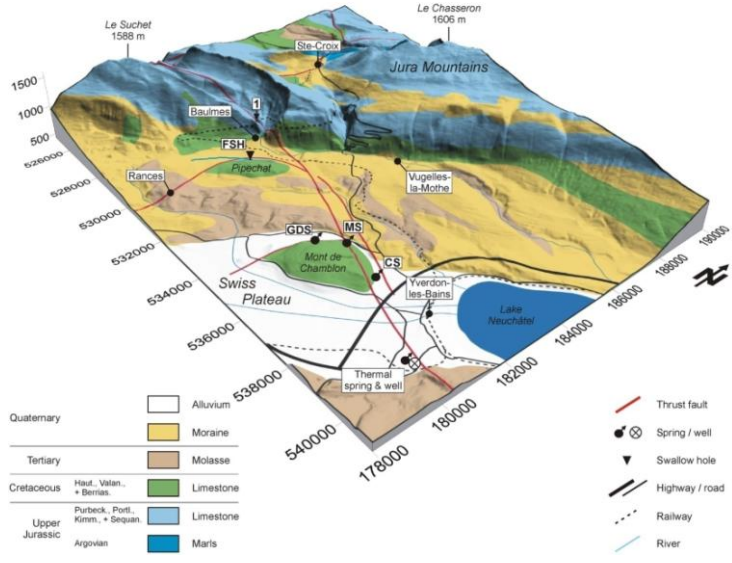
M Moulinet springs

Q = 20 - 700 L/s

C Cossaux spring

Q = 40 - 90 L/s

Block Diagram of the Study Area



Block Diagram: Francois Gainon

First tracer test in 2003 – injection and sampling

Injection of 1 kg of uranine in the swallow hole …

… sampling at the springs
(automatic sampler at Moulinet 6B)

Nico Goldscheider, Michiel Pronk

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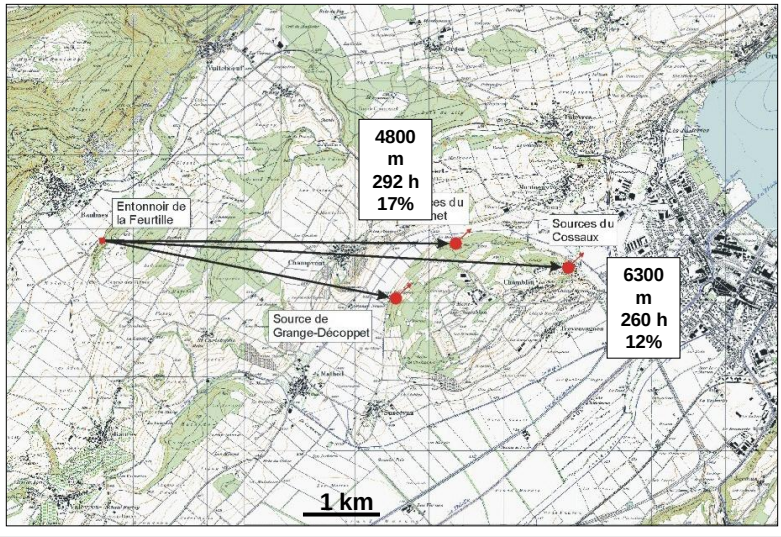
Demonstrated underground connections and transit times during extreme low-flow conditions



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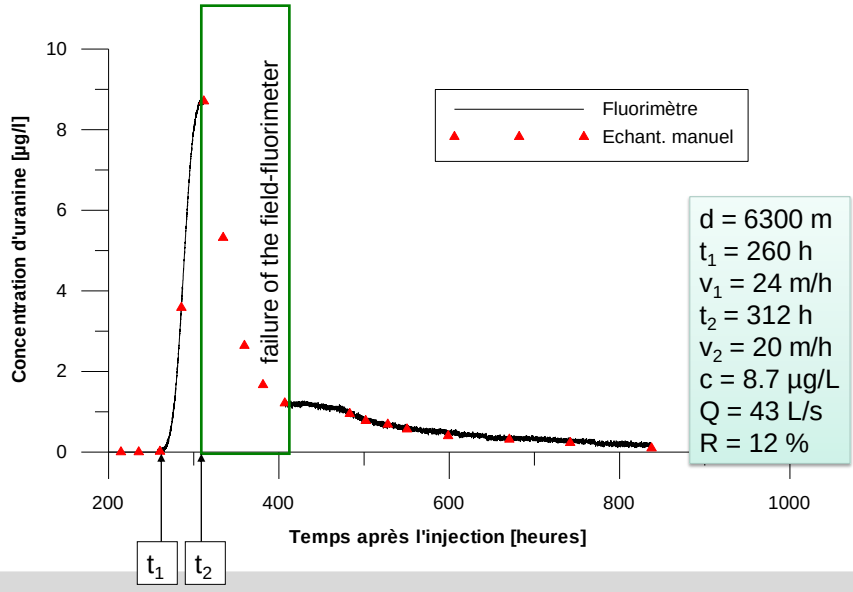
Uranine breakthrough curve, Cossaux spring



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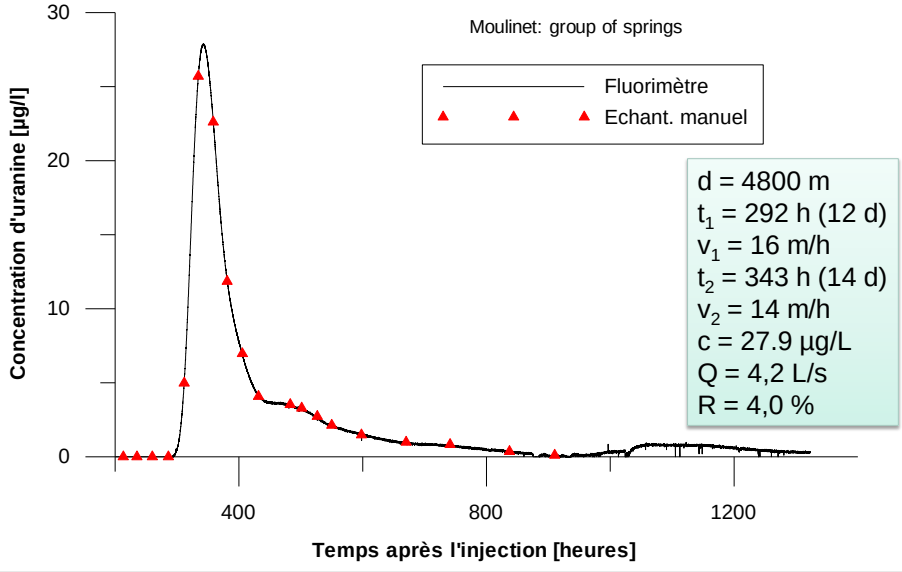
Uranine breakthrough curve, Moulinet 6A spring



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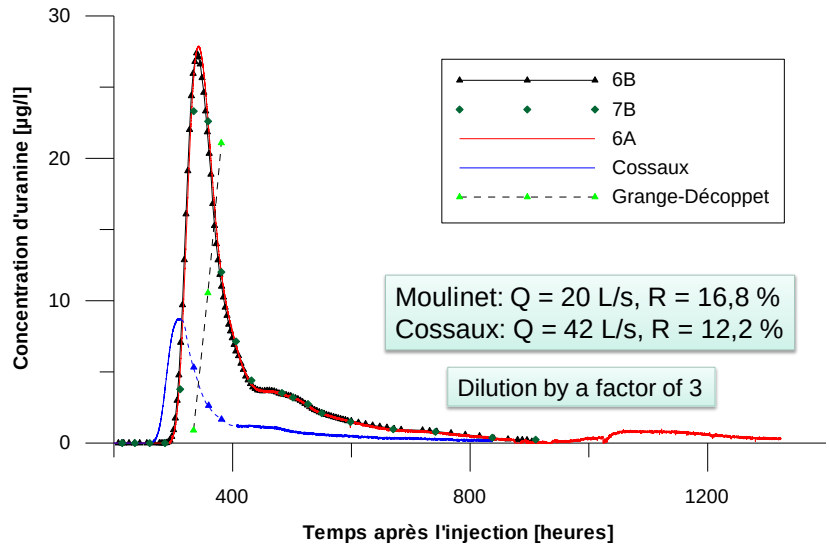
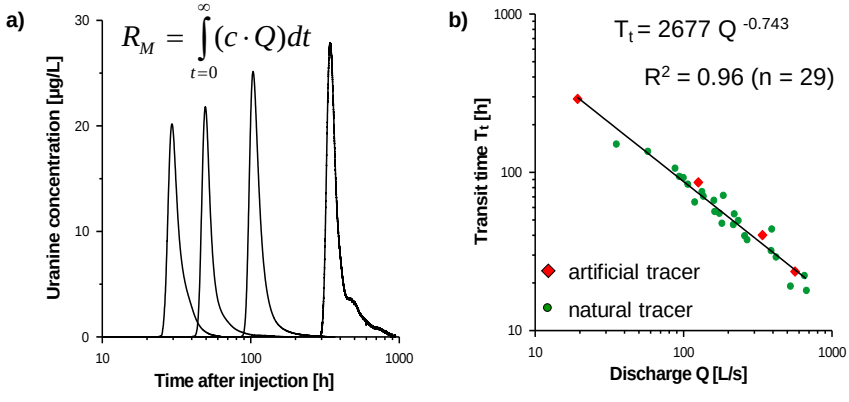
Results of the tracer tests – synopsis



Tracer tests and transit times

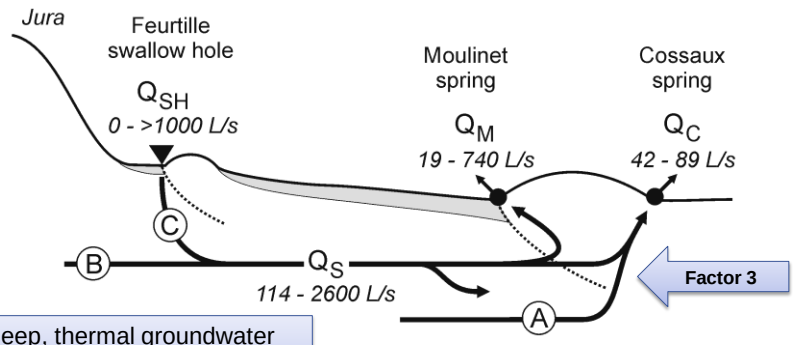
a) Results of 4 tracer tests (uranine) between the swallow hole and the springs, from low flow to high flow.

b) Relation spring discharge – transit time (1 to 14 days).



R_M: recovery, c: concentration, Q: discharge, t: time

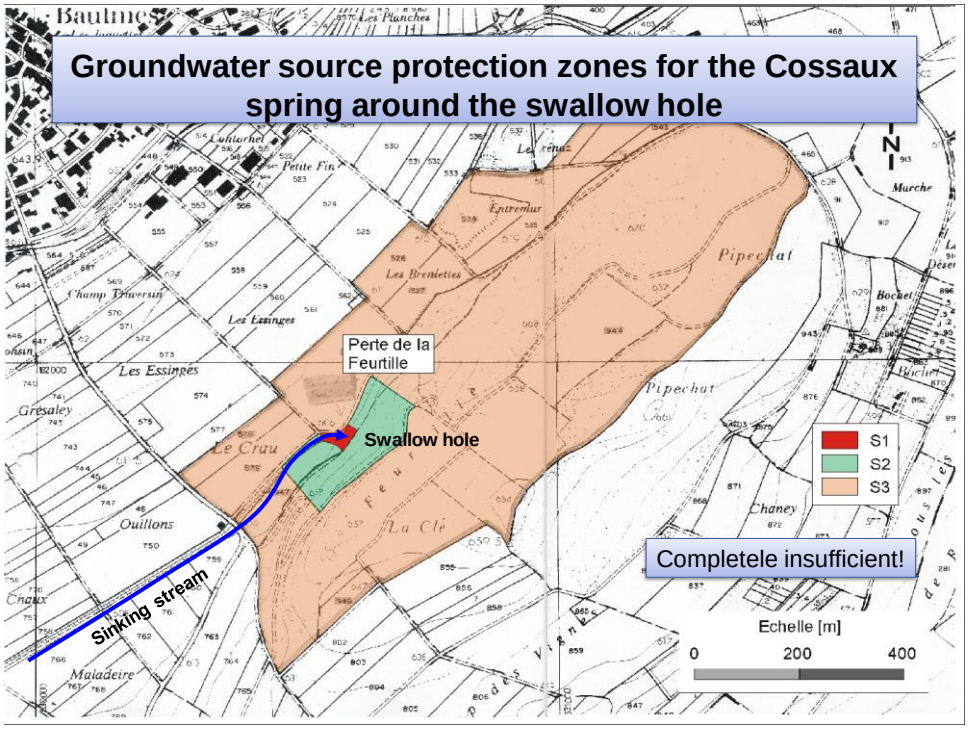
Conceptual model of the karst system (profile)



A: deep, thermal groundwater
B: water from main karst aquifer
C: swallow hole

- Range of flow rates (L/s) during low- to high-flow conditions.
- The underground system flow (Q_S) was calculated by means of water and tracer mass balance equations.

31 Pronk, Goldscheider & Zopfi, 2006, 2009

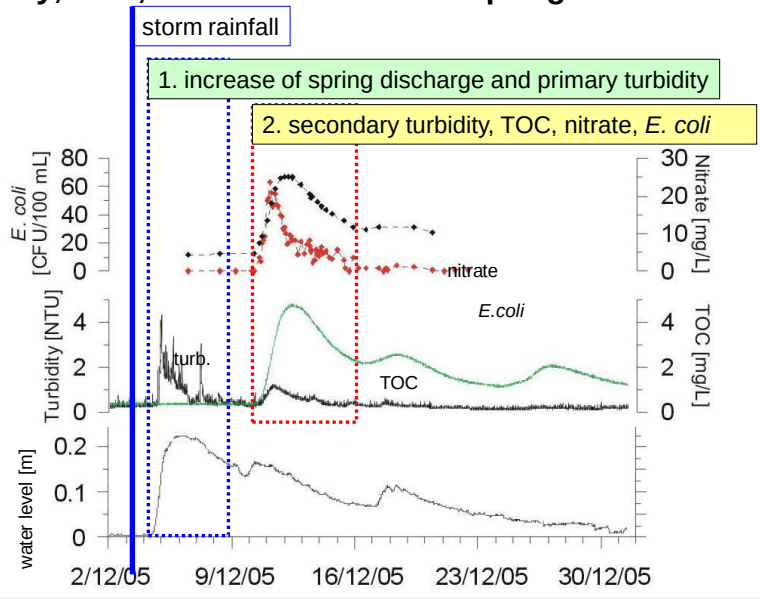


Two types of turbidity were observed in the karst spring water after intense rainfall:

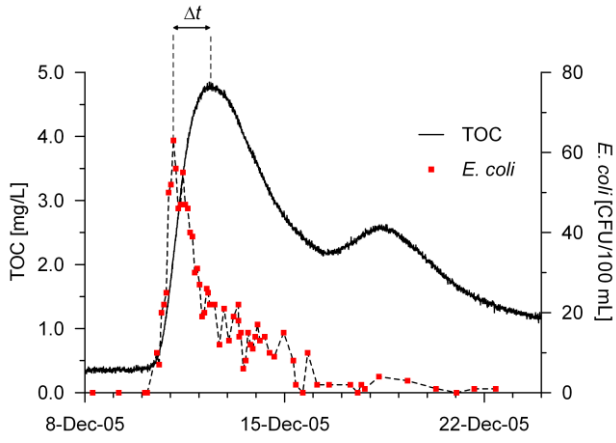
1. Primary turbidity signal: remobilization of sediments from karst conduits (***autochthonous, pulse-through***).
2. Secondary turbidity signal: turbid water from the land surface and swallow hole (***allochthonous, flow-through***).

➔ Fecal and pathogenic bacteria, organic carbon (TOC) and nitrate also originate from the land surface, i.e. they are also ***allochthonous***.

Turbidity, TOC, nitrate and *E. coli* in spring water

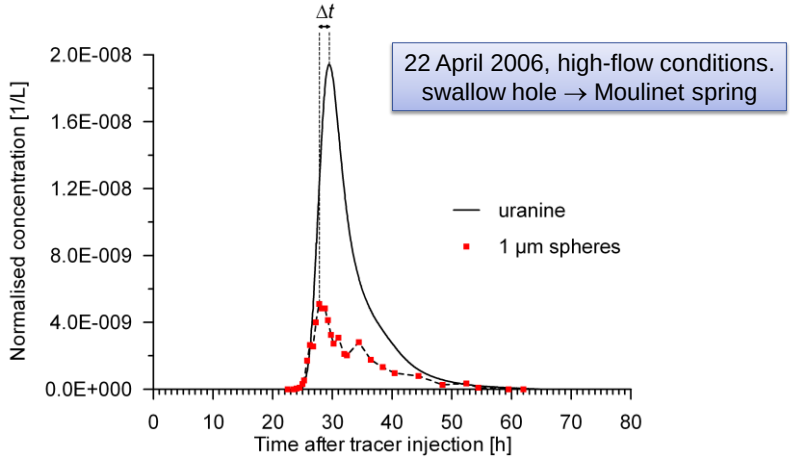


TOC and *E. coli* often occur together...



... but TOC tends to arrive slightly after the bacteria.

Comparative tracer test with uranine and microspheres (1 µm ~ similar size as *E. coli*)



Also in this case, the particles seem to arrive before the solutes!

Additional parameter: Particle-Size Distribution, PSD

- Particle Counter (Abakus mobil fluid, Markus Klotz GmbH)
- 32 particle-size classes, from 0.9 to 140 µm

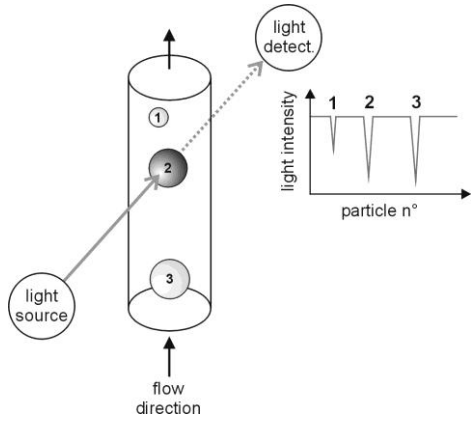
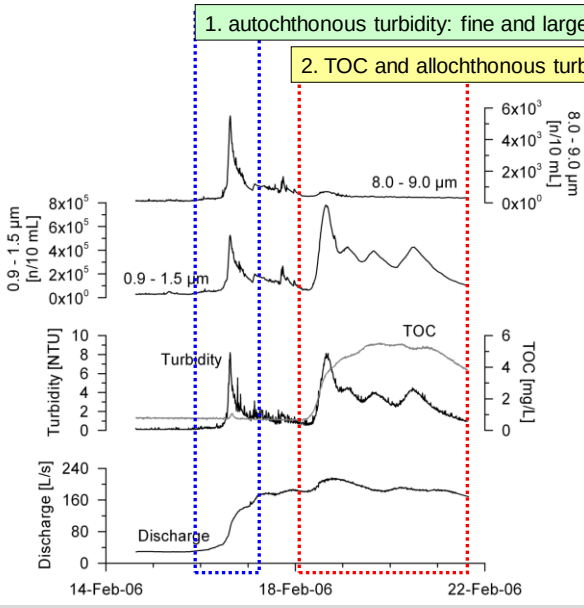


Photo: M. Klotz GmbH

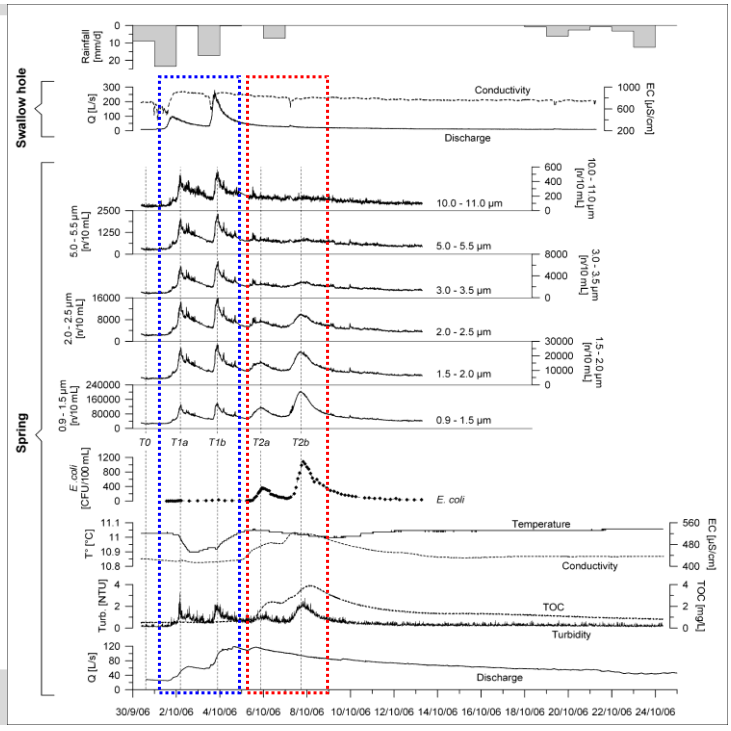
Variability of different particle-size classes following a storm rainfall event



Reason: only fine particles (and TOC) travel directly from the swallow hole to the spring; large particles are sedimented.

Double rainfall event

2 autochthonous and **2 allochthonous** turbidity signals



Pronk, Goldscheider & Zopfi (2007)

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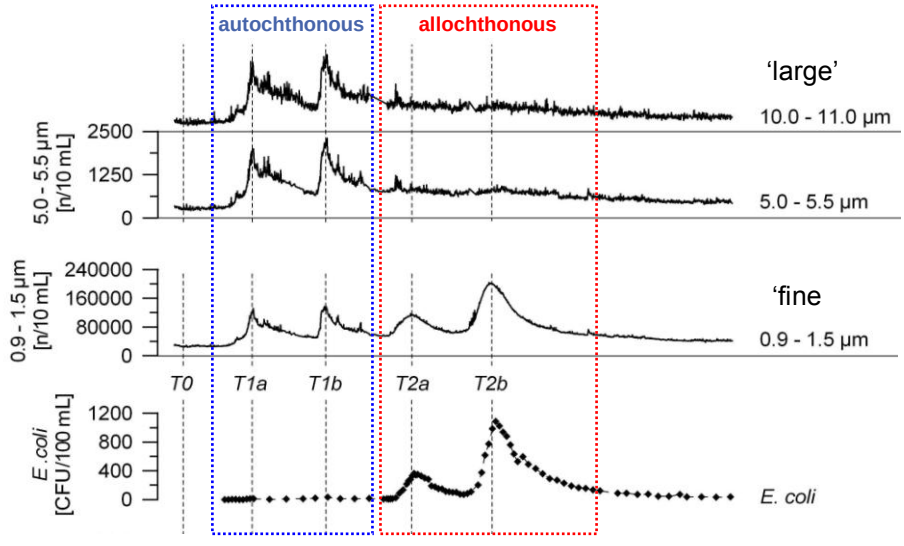
Details of the four turbidity signals



E. coli **~ 1 µm particles: R^2 = 0,93**

Pronk, Goldscheider & Zopfi (2007)

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Conclusions of this study

1. Turbidity in the spring water either comes from a remobilization of sediments from inside the karst aquifer (autochthonous) or from the land surface (allochthonous);
2. Allochthonous turbidity is often associated with increased levels of fecal bacteria (pathogens) and organic carbon;
3. The simultaneous increase of TOC and turbidity indicates possible microbial contamination.
4. Particle-size distribution (PSD) makes it possible to even better differentiate the two types of turbidity;
5. A relative increase of fine particles (~ 1 µm) indicates allochthonous turbidity and, thus, microbial contamination.

➔ **Two "early-warning systems" for microbial contamination:**

(1) Simultaneous increase of TOC and turbidity

(2) PSD: Relative increase of fine particles

41 Pronk, Goldscheider & Zopfi (2007)

General Conclusions

Save drinking water from karst aquifers or other freshwater resources, requires a fourfold approach:

1. Minimizing pollution: wastewater treatment, repair leaking sewage pipes, reduced and sensible use of liquid manure, etc.
2. Groundwater protection zoning: land-use restrictions in the most vulnerable zones.
3. Water quality monitoring: karst springs require event-based, intelligent monitoring strategies (early-warning systems).
4. Drinking water treatment: filtration, chlorination, ozone, UV treatment, etc.

Ideally, all four elements should be present, but if some elements are not feasible, the other elements should be done very well.

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Selected References

Benischke R, Goldscheider N, Smart C (2007) Tracer techniques. In: Goldscheider N & Drew D (Eds.) Methods in Karst Hydrogeology. London: Taylor & Francis: 147-170.

Goldscheider N, Meiman J, Pronk M, Smart C (2008) Tracer tests in karst hydrogeology and speleology. International Journal of Speleology, 37(1): 27-40.

Goldscheider N, Drew D (2007) Methods in Karst Hydrogeology. International Contributions to Hydrogeology, 26. London, Taylor & Francis, 264 p.

Göppert N & Goldscheider N (2008) Solute and colloid transport in karst conduits under low and high flow conditions. Ground Water, 46(1): 61-6

Pronk M, Goldscheider N & Zopfi J (2006) Dynamics and interaction of organic carbon, turbidity and bacteria in a karst aquifer system. Hydrogeology Journal.

Pronk M, Goldscheider N, Zopfi J (2007) Particle-size distribution as indicator for fecal bacteria contamination of drinking water from karst springs. Environmental Science & Technology, 41(24), 8400-8405.

Pronk M, Goldscheider N, Zopfi J (2009a) Microbial communities in karst groundwater and their potential use for biomonitoring. Hydrogeology Journal, 17(1): 37-48.

Pronk, M., Goldscheider, N., Zopfi, J. & Zwahlen, F. (2009b): Percolation and particle transport in the unsaturated zone of a karst aquifer. Ground Water, 47(3): 361-369.

Complete publications list: http://publicationslist.org/nico.goldscheider