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percorsi di idrogeologia

Challenges and Advances in Karst Hydrogeology

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1. Prologue: Amazing and Instructive Example

Tom Morris and *Jill Heinerth* prepare to dive into a cave spring used for drinking water supply in Florida, USA.

Photos of this example: Wes Skiles / Karst Productions

The diving team carries a specialized “Cave Radio” to allow their movements to be tracked from the surface.

The “Surface Team” carries a corresponding receiver.

The cave follows underneath and below an industrial storage facility, and then the salad bar of a local restaurant.

The subterranean path of the divers leads underneath a trash-filled sinkhole…

...where they re-emerge.

Several lessons can be learned from this example

- Conduits and caves are crucial for groundwater flow and for contaminant transport in karst aquifers;
- There might be large conduits and water caves even when there are no surface karst landforms;
- Karst aquifers require specific investigation techniques;
- Karst aquifers also offer unique opportunities to study groundwater flow and contaminant transport, such as the direct access of the aquifer via dry or water-filled caves;
- Don’t use dolines and sinkholes as waste dumps!

2. Hydrogeology and Vulnerability of Karst Aquifers

- 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.

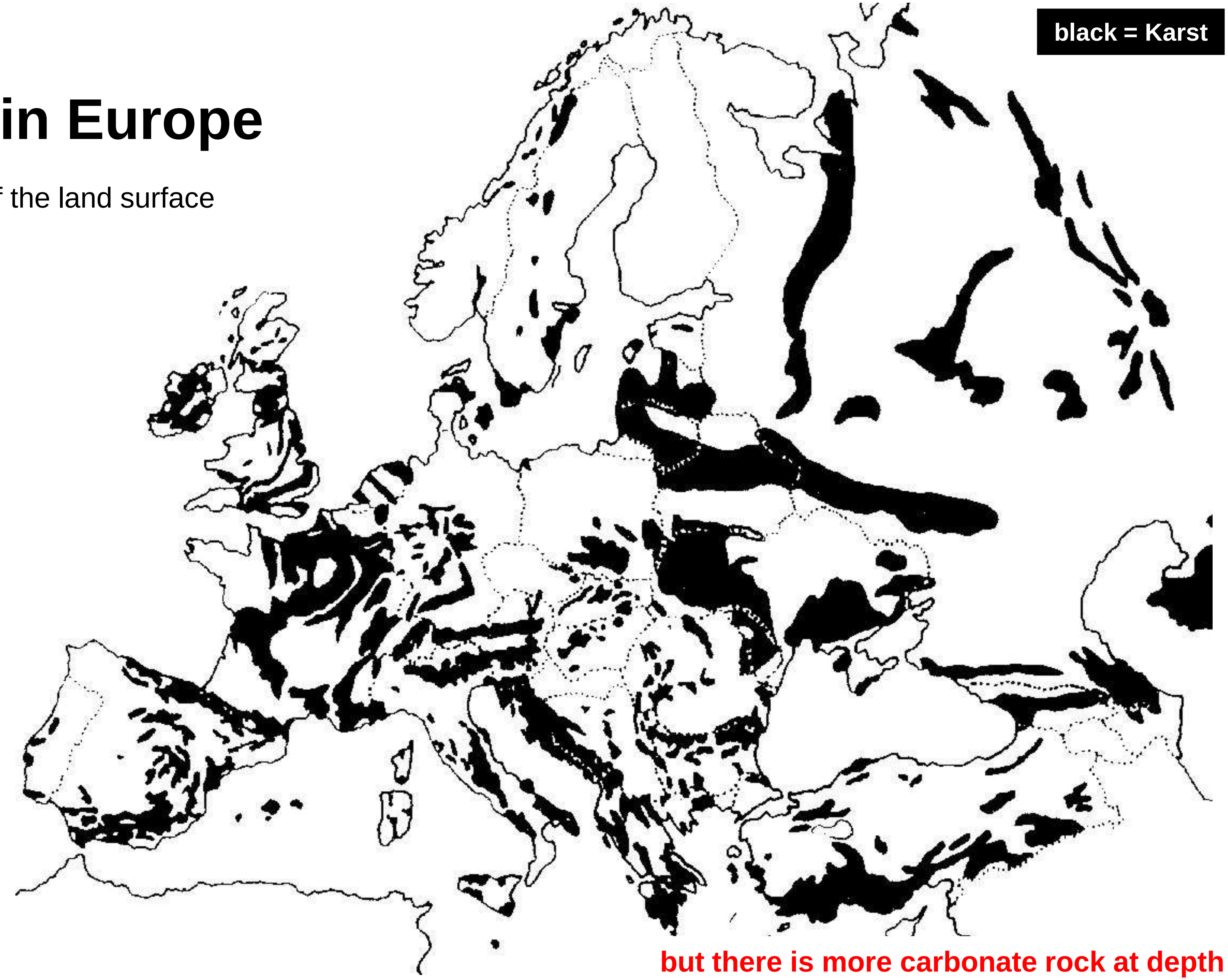
Wastewater injection into an alpine karst aquifer

Drinking water drainage gallery in an alpine karst aquifer

all photos and figures without other reference: Nico Goldscheider

Karst in Europe

35 % of the land surface



but there is more carbonate rock at depth

COST 65, 1995

Karst: Large areas without surface drainage

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

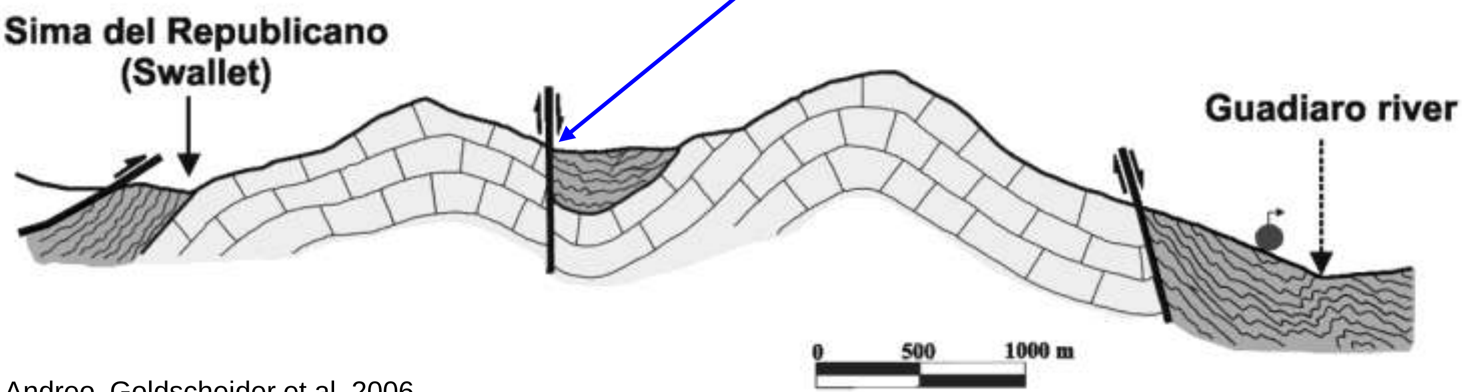
- Rapid infiltration through thin soils and into solutionally enlarged fractures of the epikarst zone.

➔ Little protection against contamination = high vulnerability

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).

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

Reynolds number, R [-]

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

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

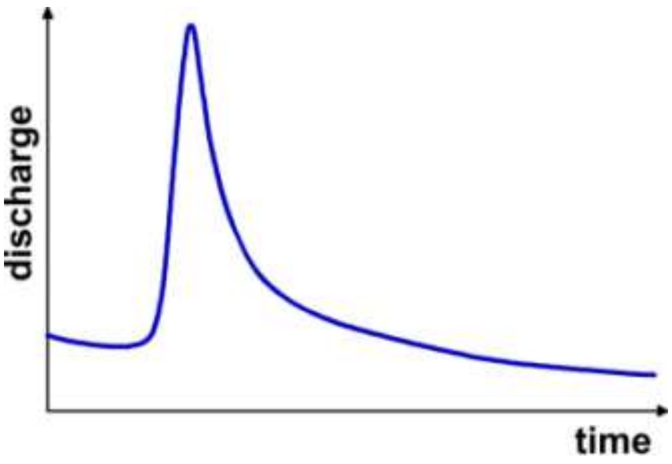
[kg, m, s]

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

… 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

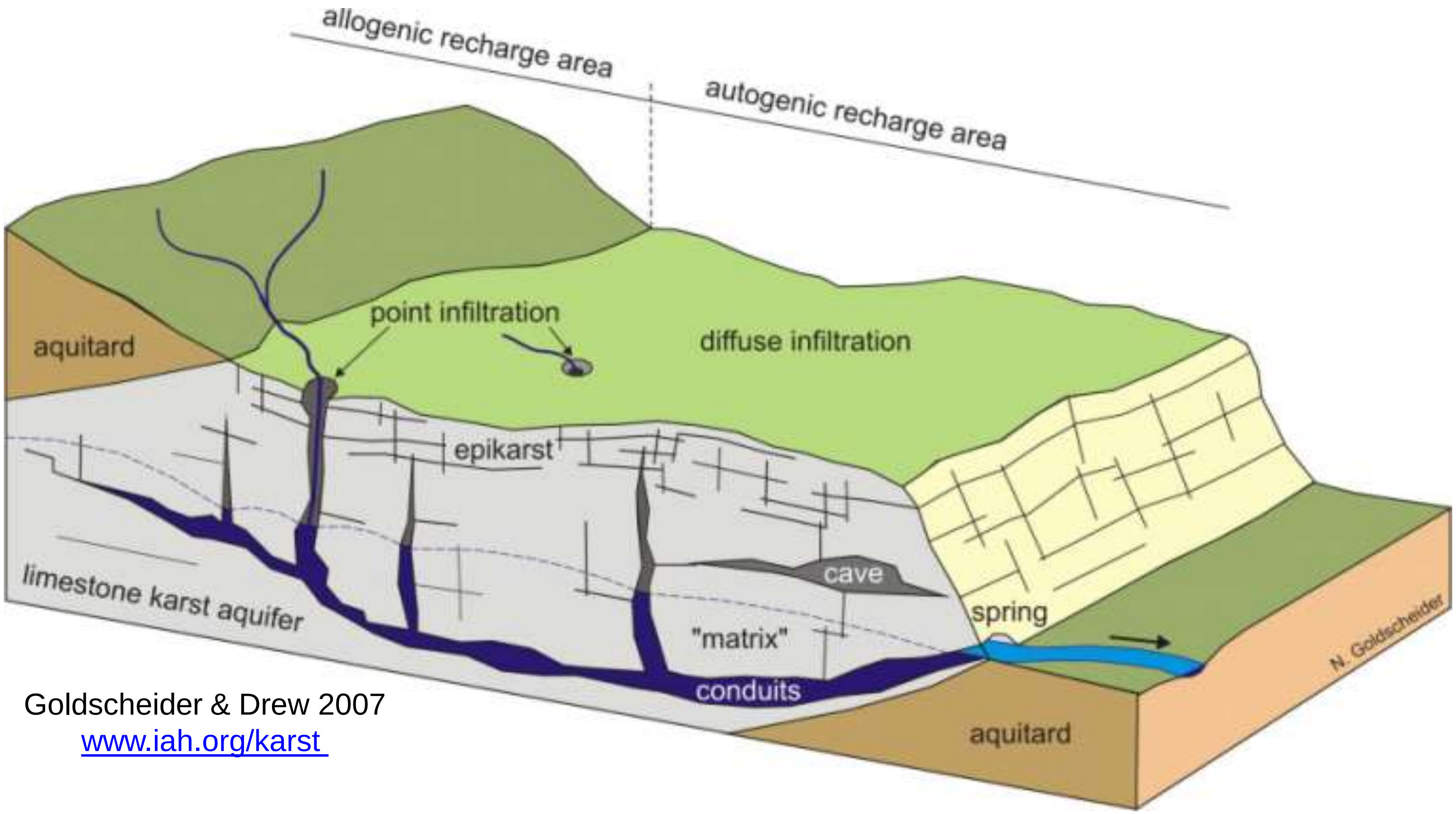
karst depression, dry

karst depression, flooded

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

photos: Nataša Ravbar

Block diagram of a karst aquifer



Goldscheider & Drew 2007
www.iah.org/karst

- Autogenic vs. allogenic recharge
- Diffuse infiltration vs. point infiltration
- Laminar matrix flow vs. turbulent conduit flow

"Duality"

➔ High degree of heterogeneity and anisotropy

“Duality” of conduits and rock matrix in nature

Spring emerging from an open cave, French Jura Mountains

High flow rates and flow velocities in the conduits, while the adjacent rock volumes can be completely unproductive.

➔ Drilled wells in karst aquifers are often unproductive.

➔ It is often better to use springs for drinking water supply.

Same spring from another perspective: flow variability

8 June 2006: high-flow conditions

8 May 2009: spring dry

3. Challenges and Research Frontiers

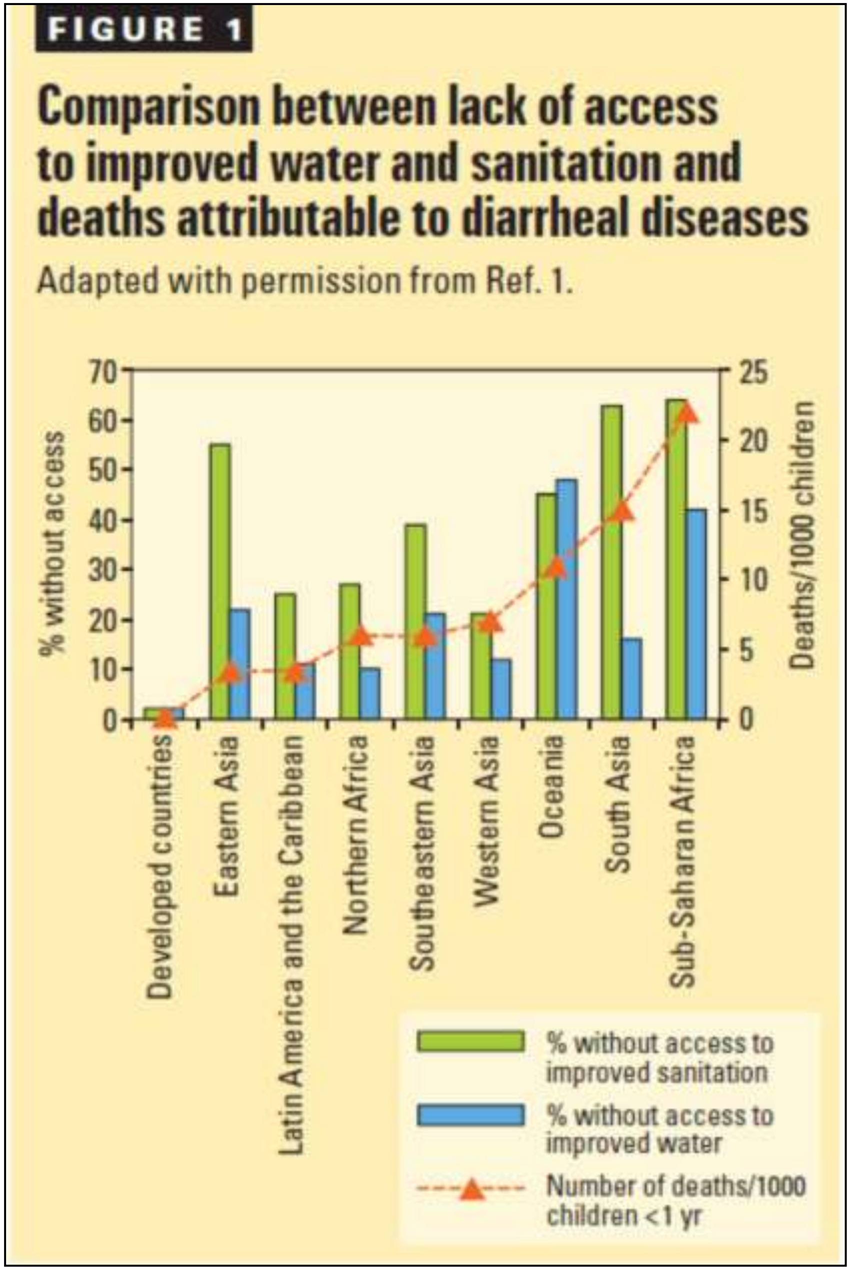
Injection of a fluorescent dye (Amidorhodamine) into Blauhöhle cave stream, Germany

Injection: Nico Goldscheider, Photo: Andreas Kücha

Major Challenge:
Safe Drinking Water

- Threatened by contamination, over-exploitation, etc.
- Water also needed for production of food and biofuels.
- Direct relation between lack of access to improved water and deaths due to diarrheal diseases.

Children in a Vietnamese karst area



→ Case Study

Challenge: Soil Erosion

Southwest China: Soil erosion and rock desertification on circa 100.000 km^2 of karst land – one of the greatest environmental challenges.

Soil erosion in SW China (photo: N. Goldscheider)

What has soil erosion to do with hydrogeology?

- Soil erosion changes groundwater recharge.
- Soil erosion means less natural protection of the aquifer, i.e. higher vulnerability of groundwater to contamination.
- Soil erosion generates turbidity, which facilitates particle-bound contaminant transport.
- Soil erosion reduces the efficiency of the soil and the karst aquifer systems as a natural sink for atmospheric CO_2.

➔ Interdisciplinary Research Frontier

This alpine area was used for cattle pasture until some hundred years ago. Soil erosion probably happened during the “Little Ice Age”.

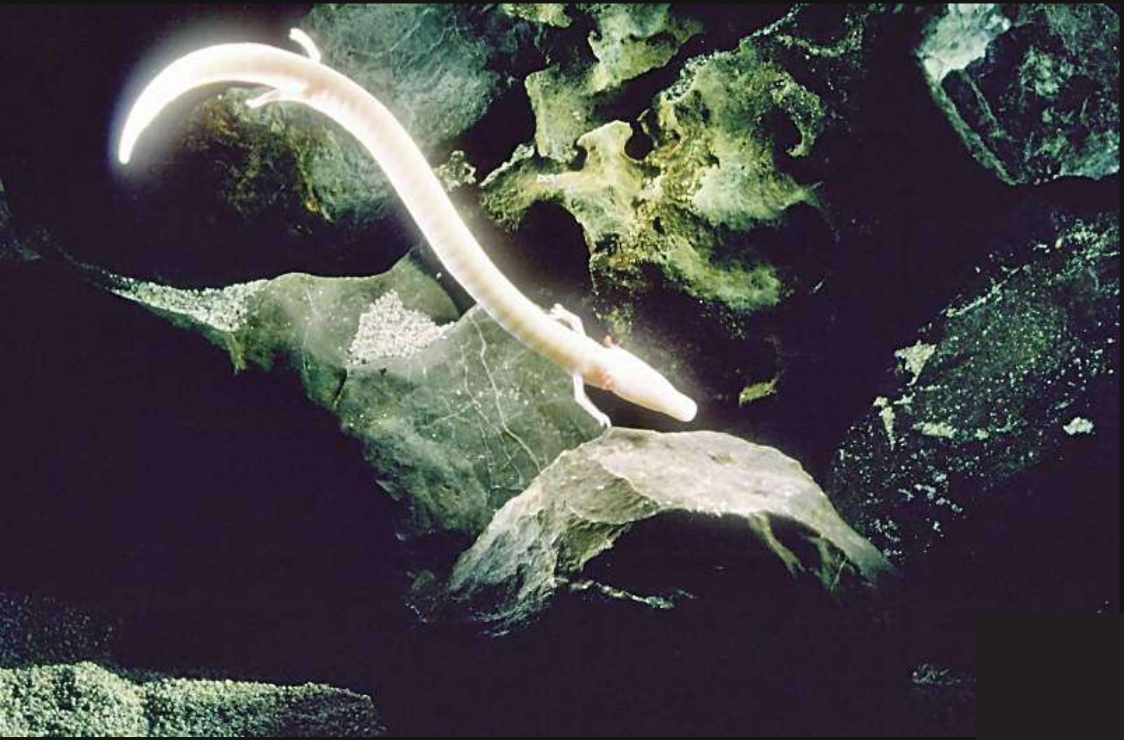
Challenge: Protection of Biodiversity

- Intense groundwater-surface water interaction in karst areas.
- Often high biodiversity at the land surface, in the epikarst, and in groundwater dependent ecosystems.
- High ecological and economical value.

The Plitvice Lakes, Croatia

Fern, supplied by epikarst water
(all photos: N. Goldscheider)

Biodiversity in a karst aquifer: rare and endemic species

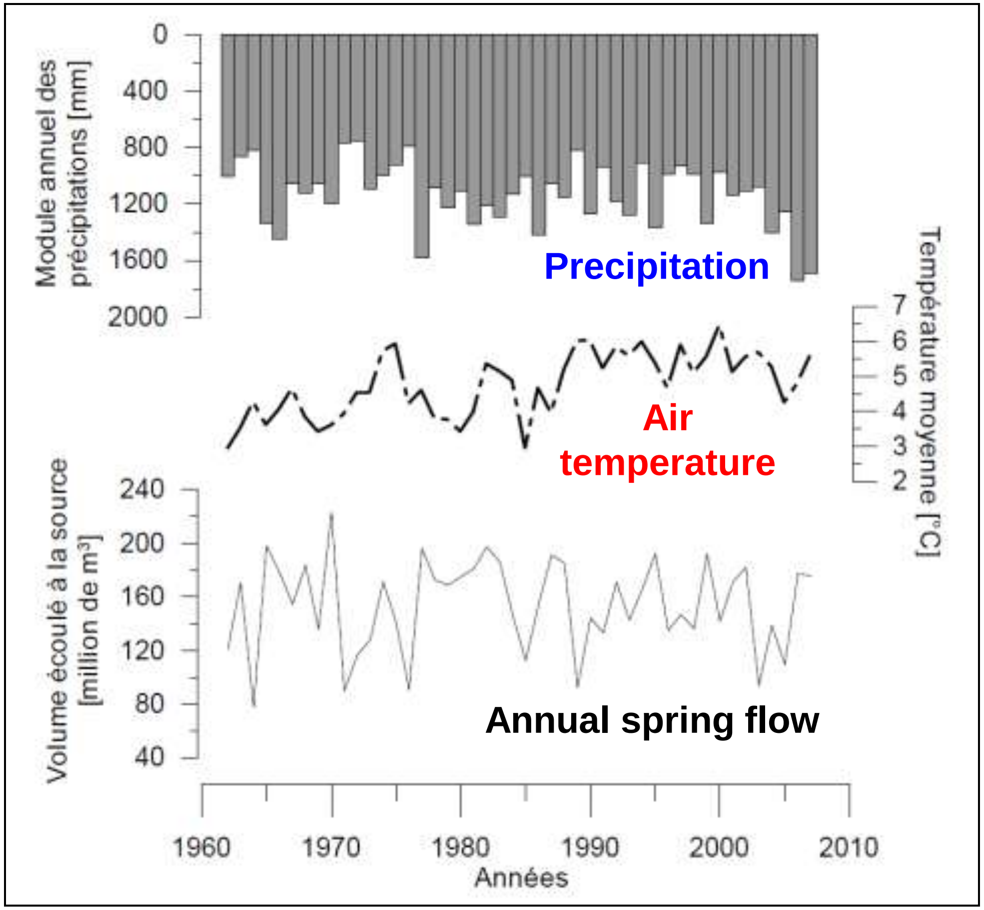


Cave Salamander (*Proteus anguinus*)
Photos: A. Hodalic

Cave Fish
(*Astyanax fasciatus mexicanus*)

Challenge: Climate change impacts on karst aquifers

Analysis of 50 years of data from a large Swiss karst spring revealed:

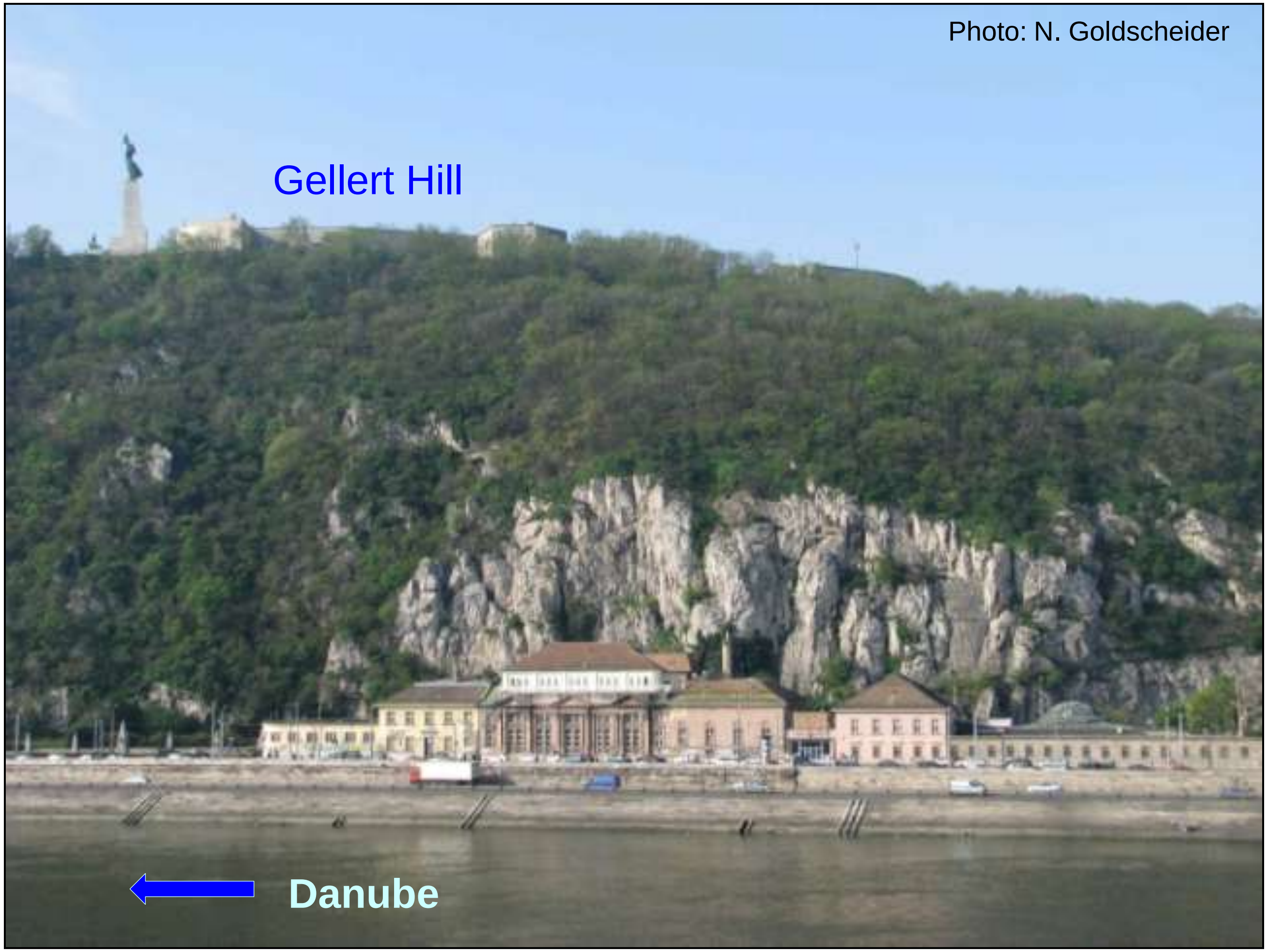


Bonnel & Goldscheider, unpublished data

- High variability
- Increasing precipitation
- Increasing air temperature
- No clear trends in aquifer recharge and spring discharge.

➔ Case Study

Challenge: Thermal water resources in karst aquifers

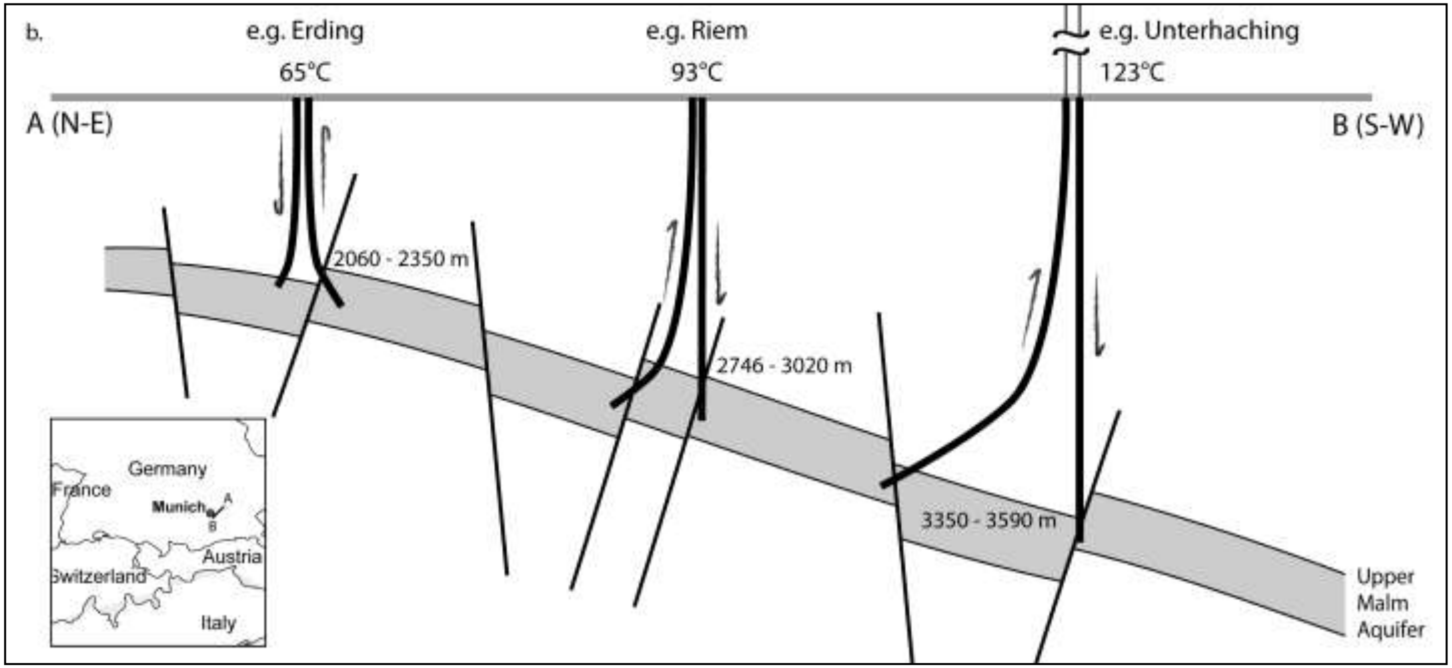


Karst aquifer outcrop and thermal bath in Budapest, Hungary

Importance of geothermal resources in karst aquifers

- Europe’s largest naturally-flowing thermal water system discharging towards spring: Budapest, karst aquifer
- Germany’s largest geothermal power station, near Munich, karst
- Most important geothermal resources apart from volcanic areas!

Geothermal karst water resource below Bavaria / Munich



Goldscheider et al. (Hydrogeology Journal, 2010)

Geothermal power station at Unterhaching near Munich

The production well at Unterhaching

- Germany’s largest geothermal power station
- Hot water from a deep carbonate rock / karst aquifer
- Drillings into fault / fracture zones, 3350 m and 3590 m deep
- Pump rate: 150 L/s; Temperature: 123 °C; Thermal power: 40 MW

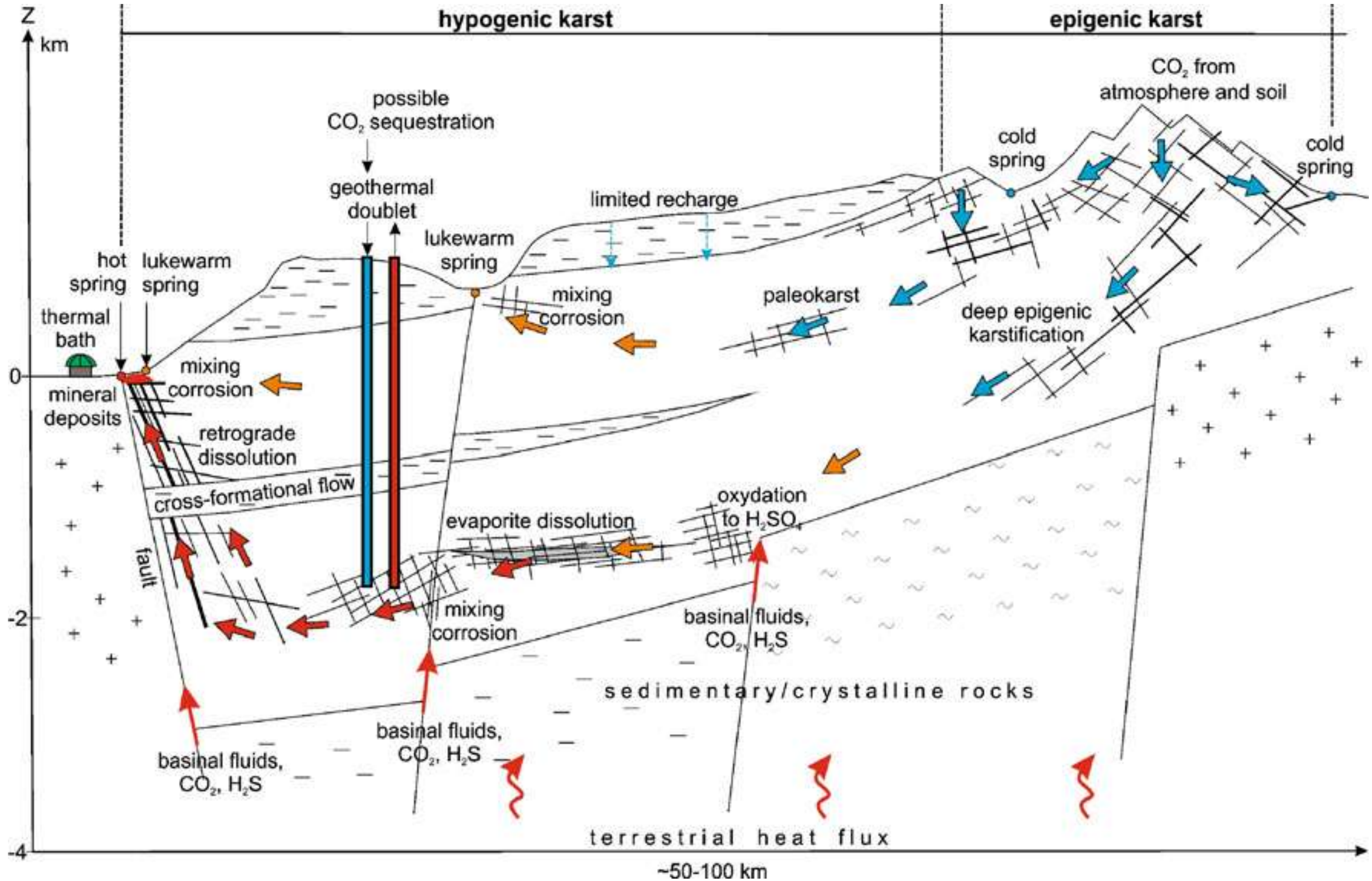
Why are karst aquifers such valuable geothermal resources?

convective heat transport by flowing groundwater	>>	conductive heat transport in rocks

- Hot groundwater is more valuable than hot (dry) rock ("groundwater makes geothermal energy efficiently utilizable")
- In most rocks, porosity and, thus, groundwater circulation strongly decrease with depth.
- Carbonate rocks: fault zones and hypogene speleogenesis create porosity at great depth, allowing for thermal water circulation.
- Deep karst aquifers are ideal natural resources for both thermal springs and geothermal energy production.
- Land consumption of geothermal power plants is very low.
- But many technical problems and also quite expensive.

Goldscheider et al. (2010)

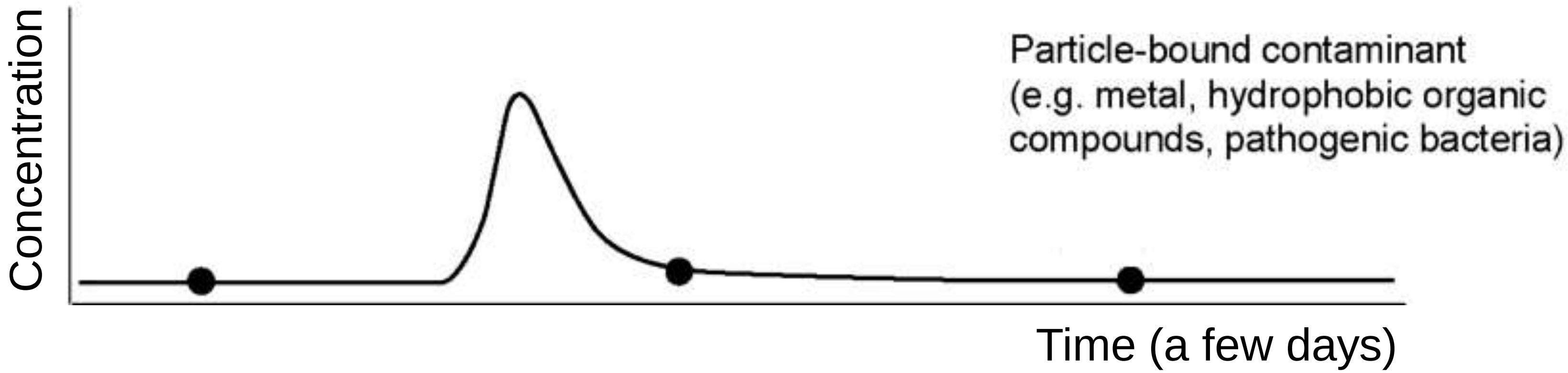
Local, intermediate and regional flow in a karst system



Goldscheider et al. (2010), inspired by Jozsef Toth

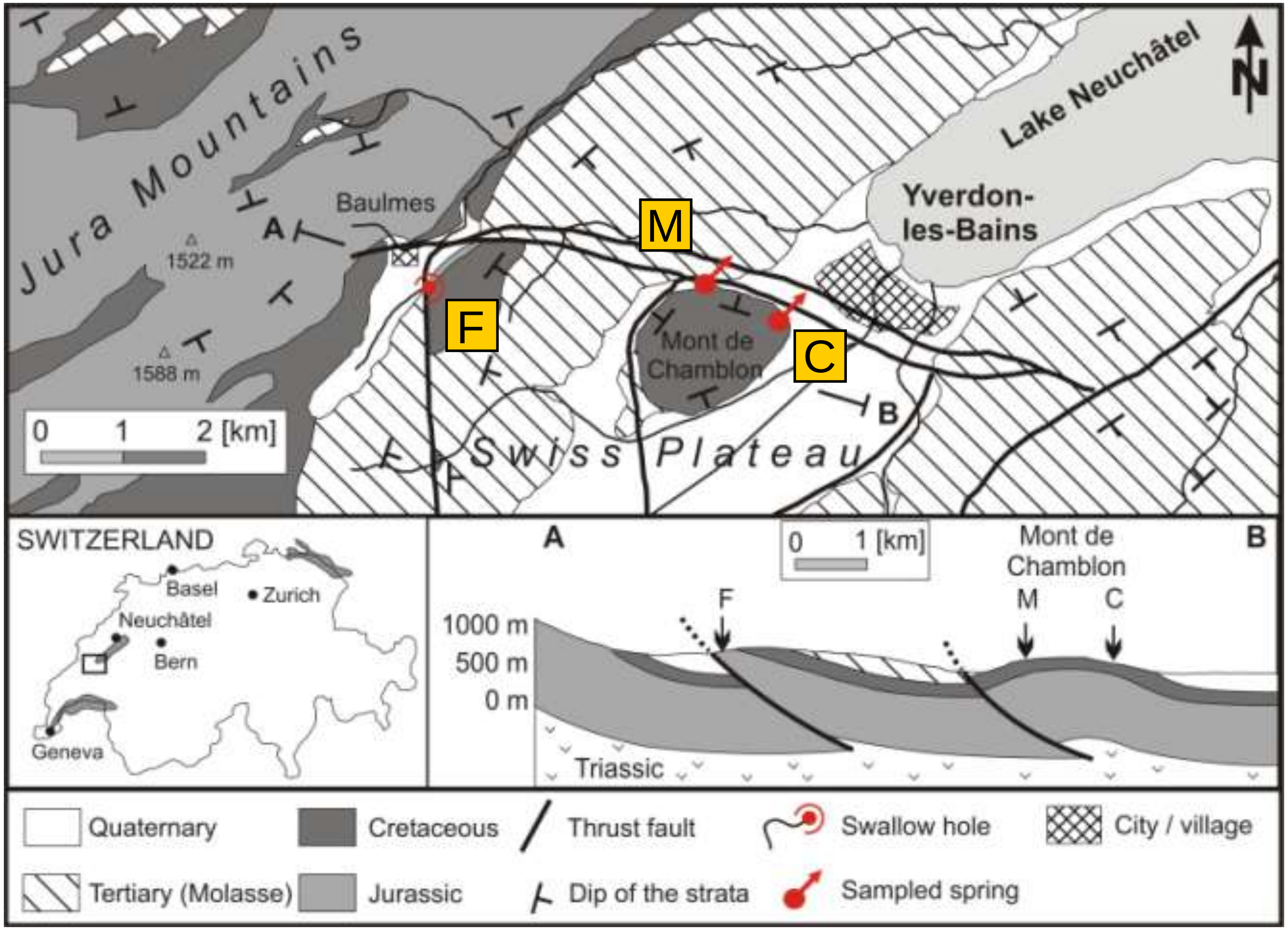
4. Early-Warning System for Microbial Contamination of Drinking Water from Karst Springs

- Long periods of good water quality are interrupted by short contamination events.
- Sampling at regular intervals (e.g. monthly) does not help.
- Continuous monitoring preferred.
- Fecal and pathogenic bacteria cannot be monitored continuously.
- We need an early-warning system for microbial contamination.



Hunkeler & Mudry, in Goldscheider & Drew (2007)

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

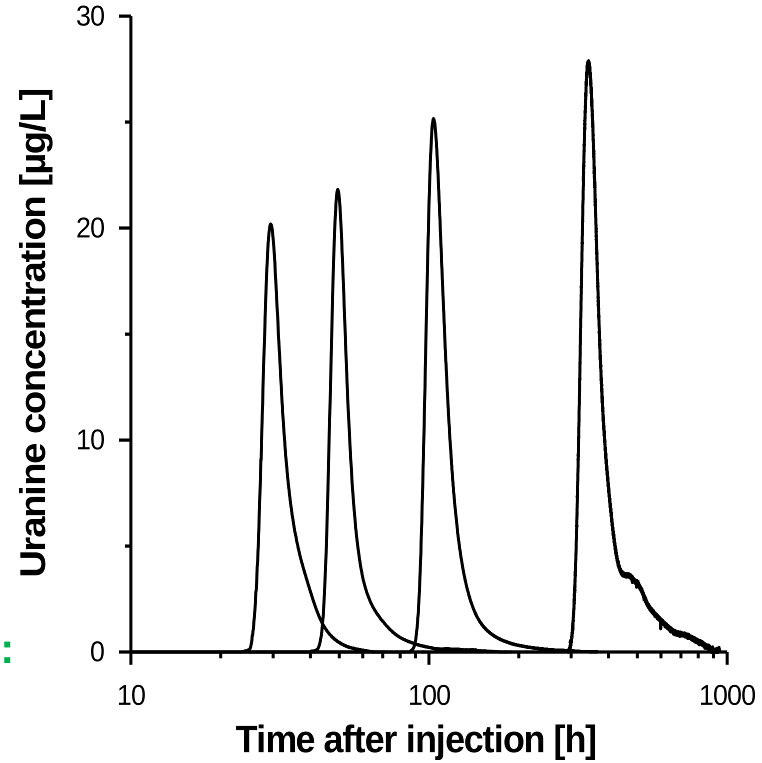
C Cossaux spring

Q = 40 - 90 L/s

Swallow hole ➔ Cossaux spring

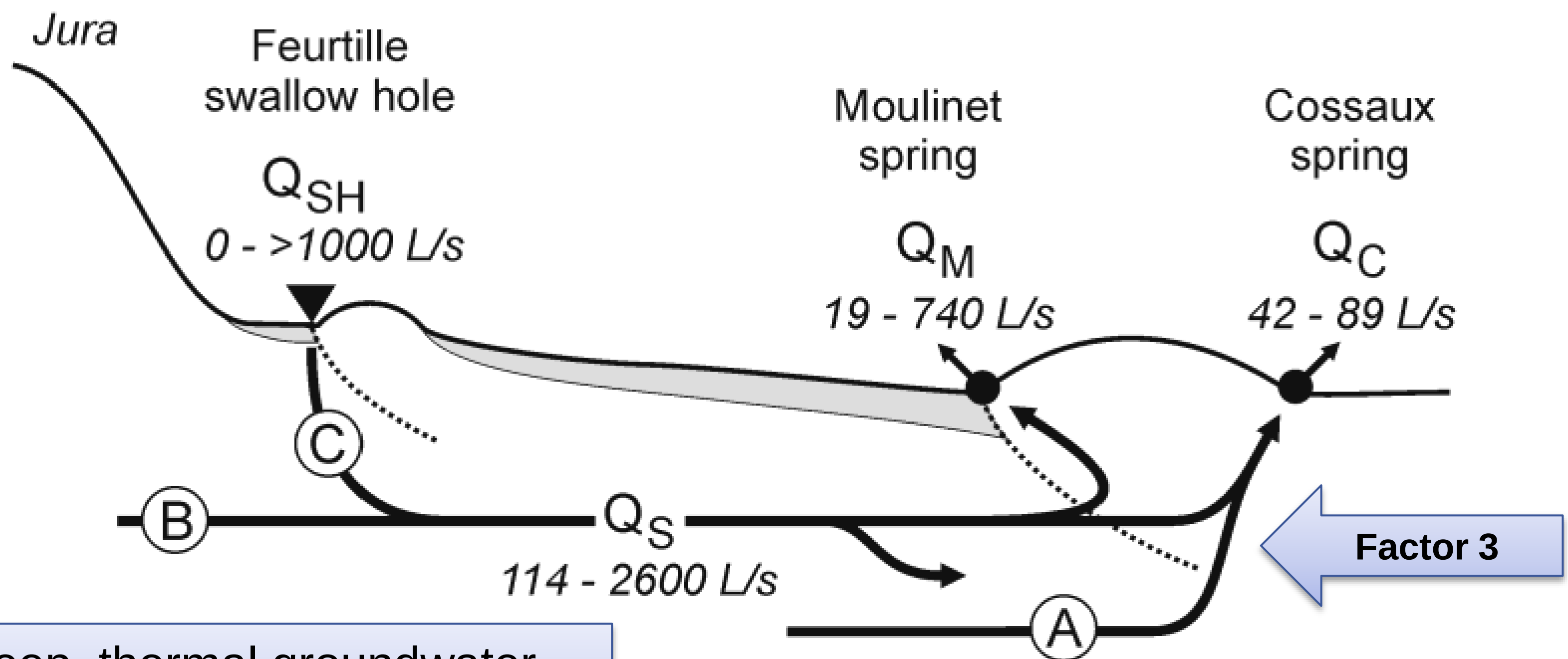
Swallow hole where surface water from agricultural land sinks into the karst aquifer

travel time
from tracer tests:
ca. 1-14 days



Cossaux spring used for drinking water supply, captured by 8 inclined drillings (no pumping)

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.

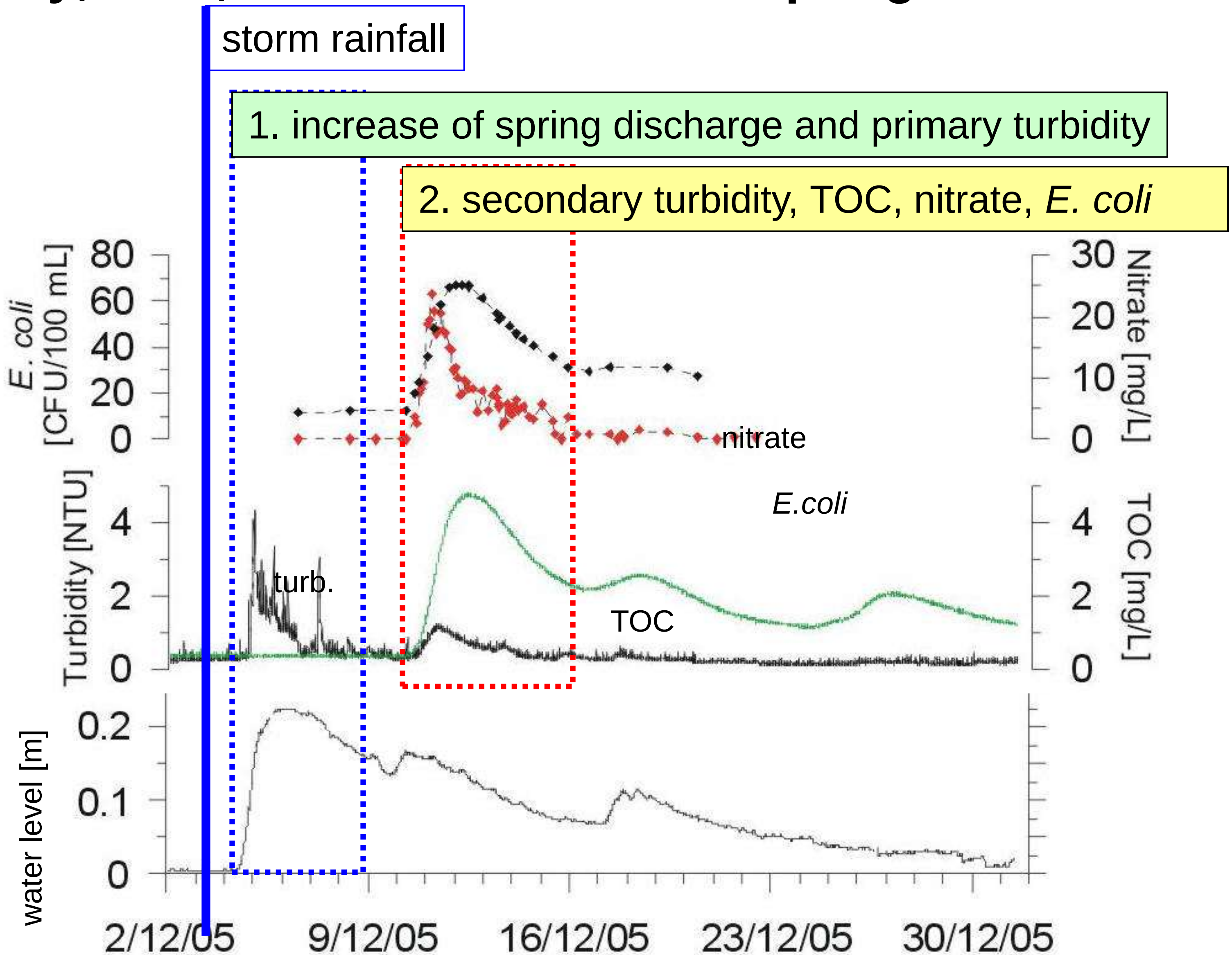
Pronk, Goldscheider & Zopfi, 2006, 2009

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 that entered the aquifer via the swallow hole (***allochthonous, flow-through***).

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

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



Additional parameter: Particle-Size Distribution, PSD

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

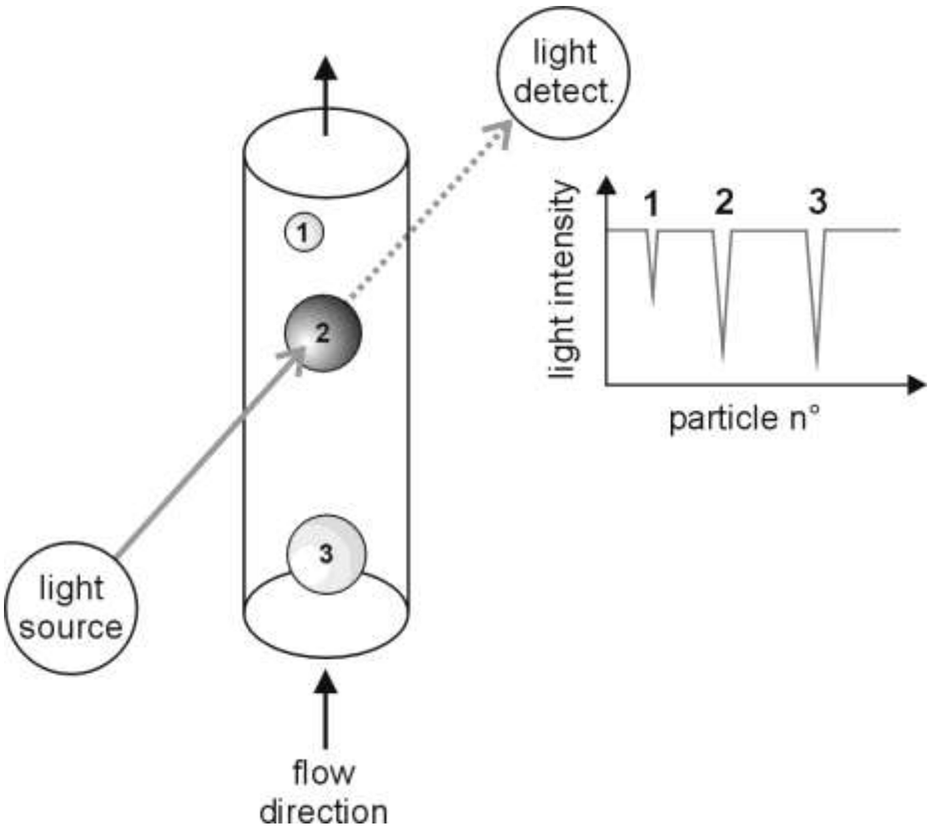
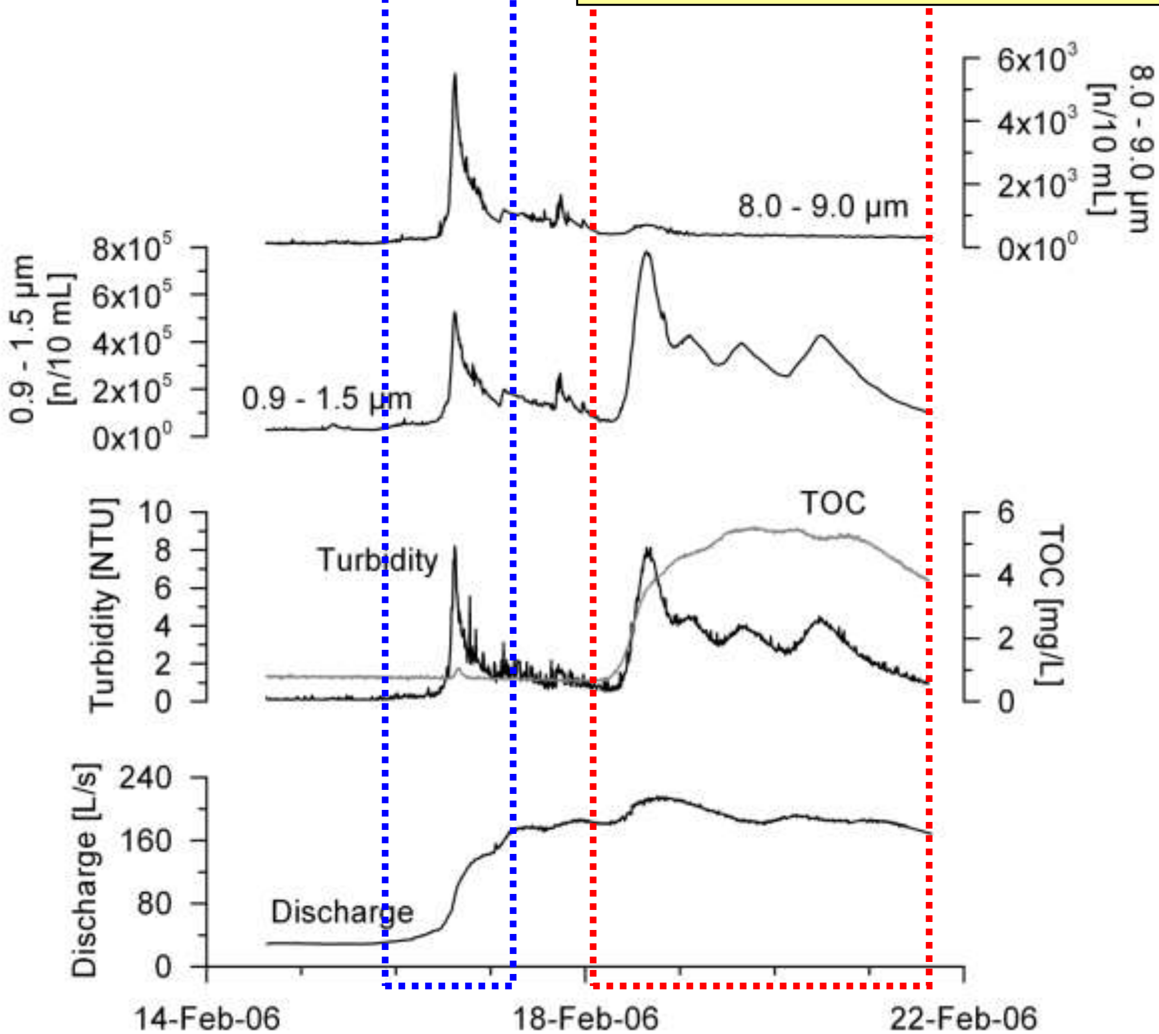


Photo: M. Klotz GmbH

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

1. autochthonous turbidity: fine and large particles

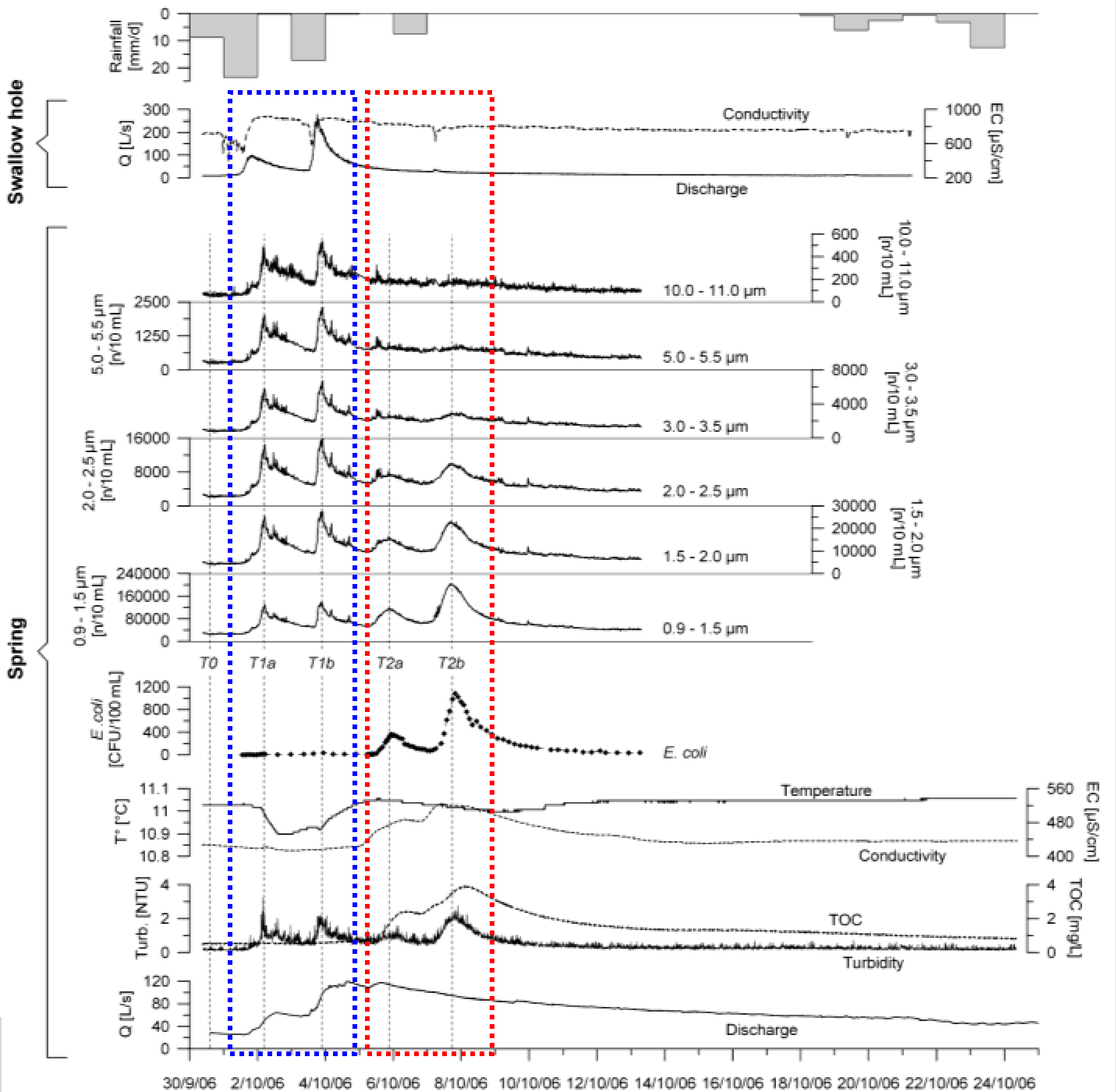
2. TOC and allochthonous turbidity: only fine particles (~1 µm)



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

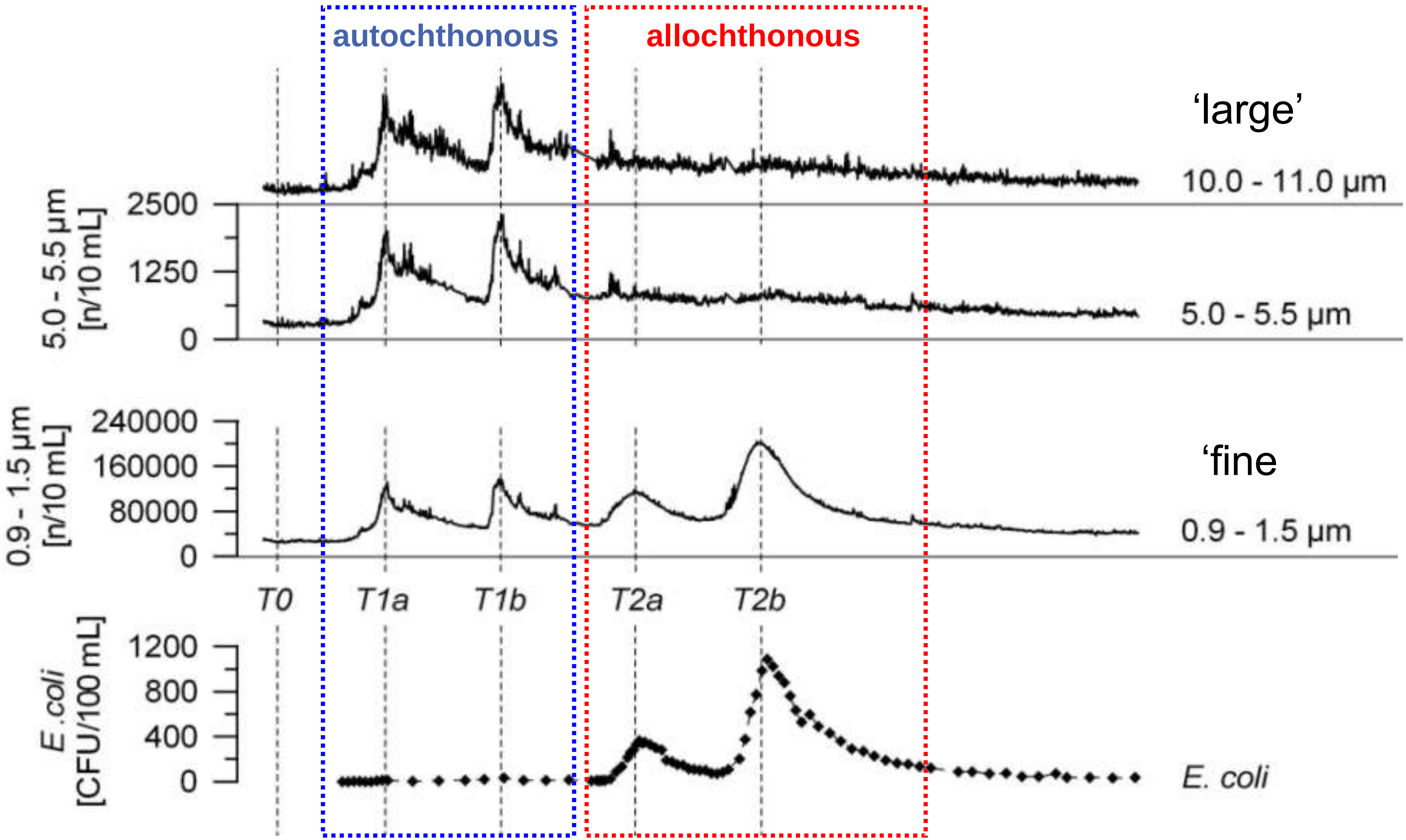
Double rainfall event

2 autochthonous
and
2 allochthonous
turbidity signals



Pronk, Goldscheider & Zopfi (2007)

Details of the four turbidity signals



E. coli ~ 1 µm particles: R^2 = 0,93

Pronk, Goldscheider & Zopfi (2007)

Result: Two possible “early-warning systems” for monitoring microbial contamination at karst springs

1. Simultaneous increase of TOC and turbidity.
2. Increase of fine particles (~1 µm) in the spring water, without parallel increase of larger particles.

➔ The first approach is now successfully used for spring water monitoring in the city of Yverdon-les-Bains.

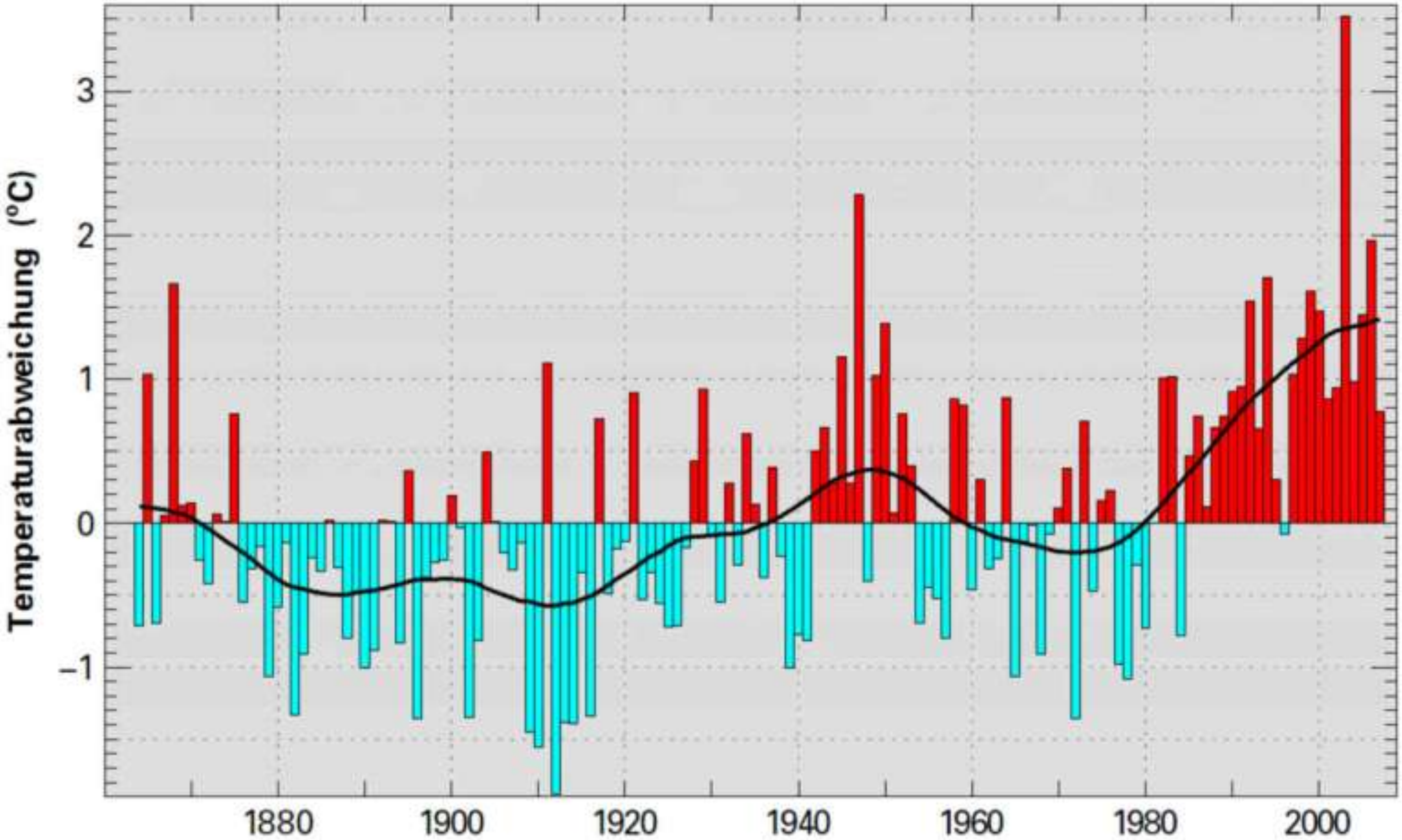
Pronk, Goldscheider & Zopfi (2006, 2007)

5. Climate Change Impacts on a Glaciated Karst System

Tsanfleuron glacier in 2009. The red number indicates the position of the glacier in 2003

Photos: Nico Goldscheider)

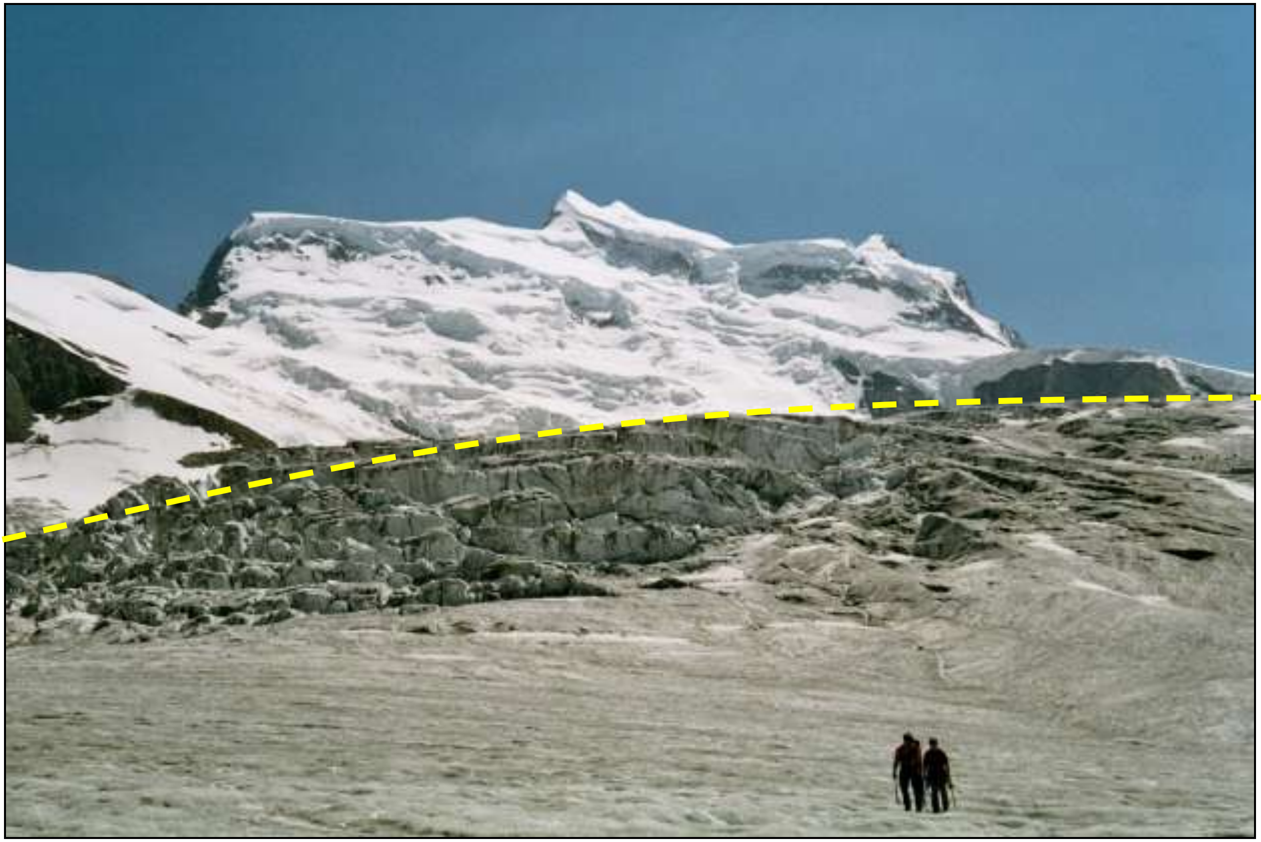
Temperatures in the Alps since 1860



2003 was 3.5°C warmer than the long-term average

Source: MeteoSuisse / OcCC (2007)

Generalities: Accumulation and Ablation Zones



Accumulation

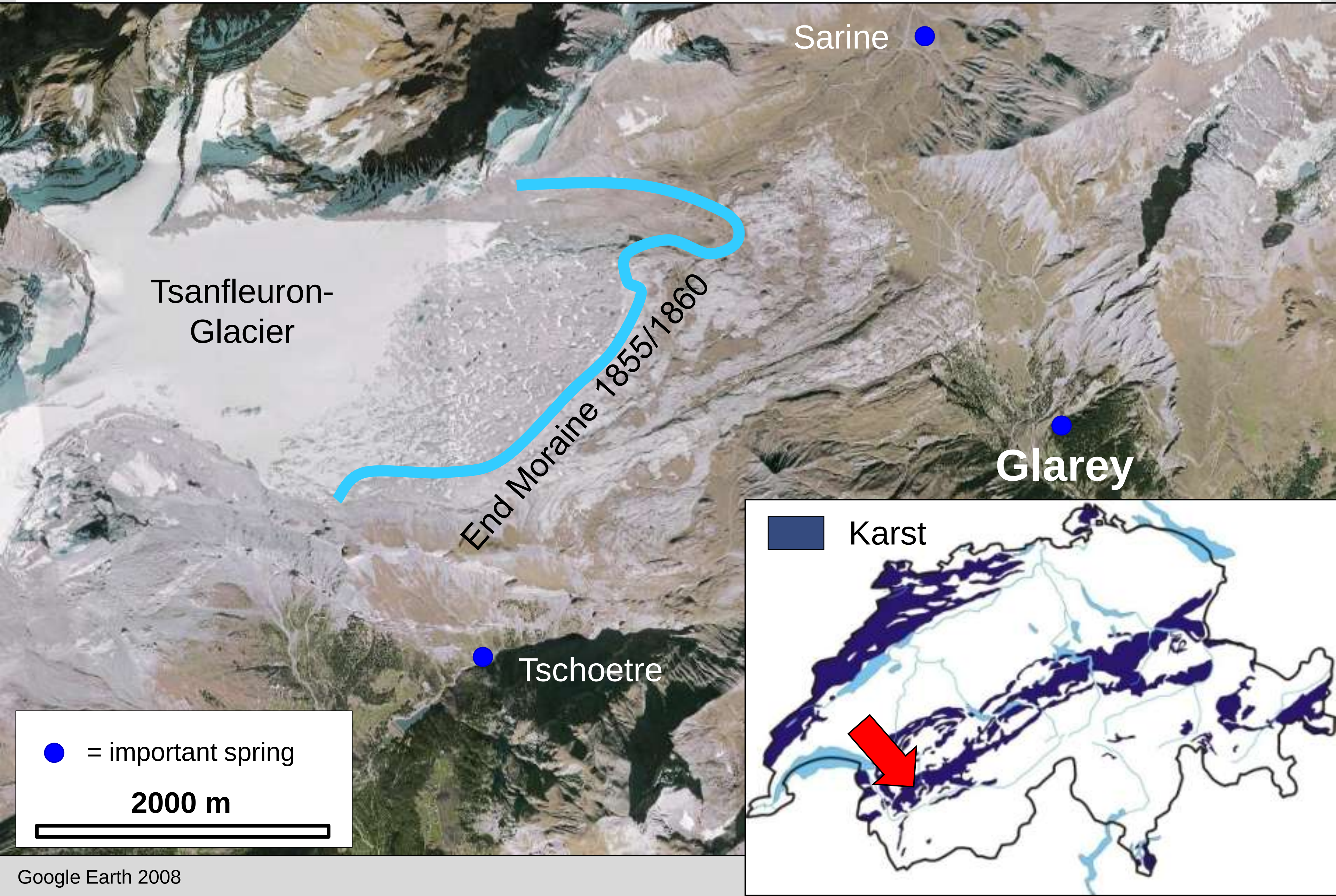
Equilibrium Line

Ablation

Glacier de Corbassière with Mt. Grand Combin (4314 m, Switzerland)

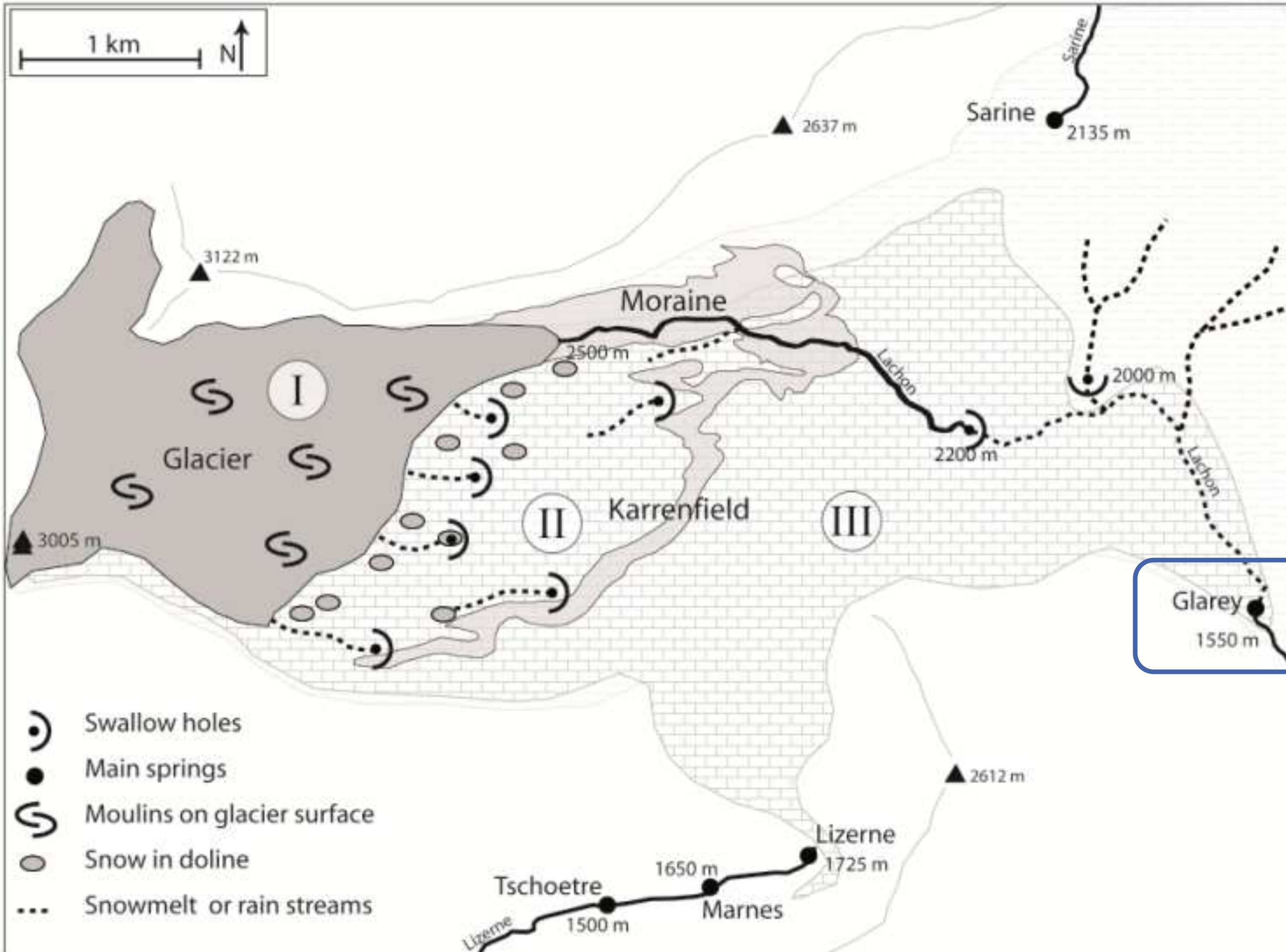
Accumulation = Ablation: glacier in equilibrium
Accumulation > Ablation: glacier advance, meltwater decrease
Accumulation < Ablation: glacier retreat, meltwater surplus

Aerial Photo: Tsanfleuron Glacier-Karst Study Site



Google Earth 2008

Karst zones, springs, surface waters, swallow holes



Zone I: Glacier on limestone (ca. 2900 m)

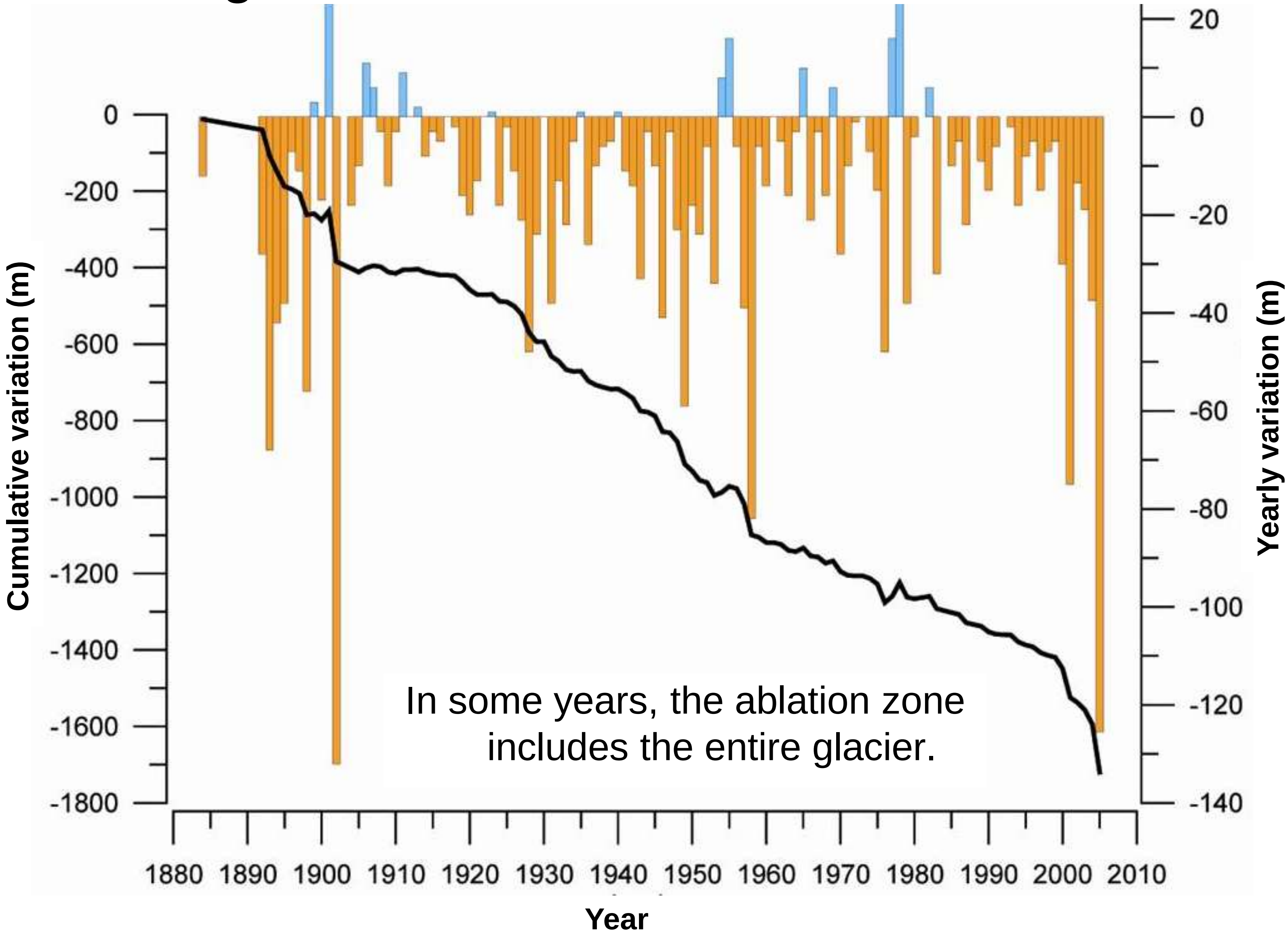
Zone II: Glacier retreat since 1855/1860, polished limestone surfaces (ca. 2650 m)

Zone III: Typical alpine karrenfields (ca. 2200 m)

Main regional spring: Source de Glarey (1550 m)

Used as a drinking water source and for irrigation

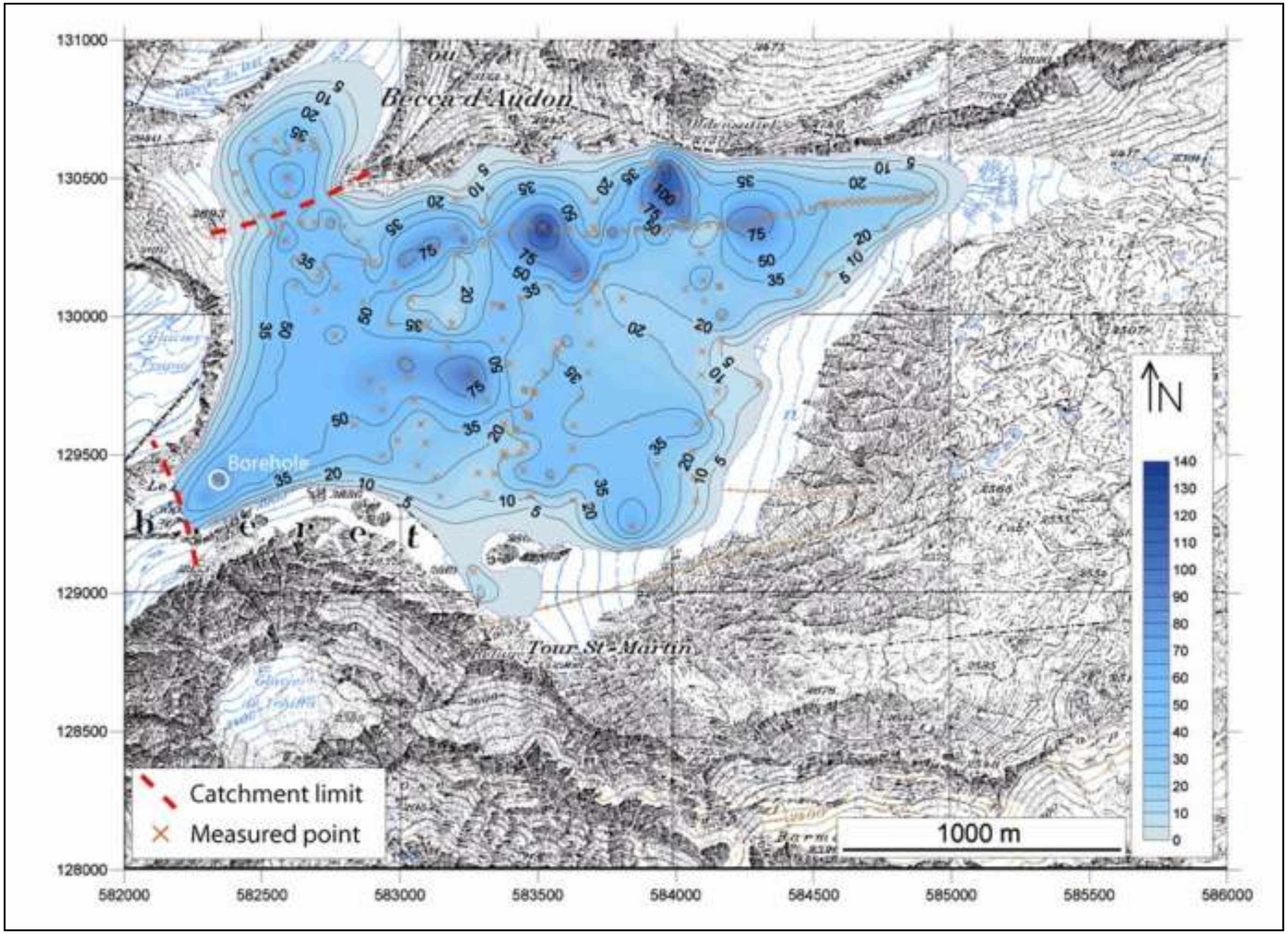
Observed glacier retreat 1884-2008: 1720 m



Source: ETH Zurich

Geophysical measurements of ice thickness using radiomagnetotellurics (RMT)

Result: Glacier thickness map



Heterogeneous pattern = subglacial karst morphology

Gremaud & Goldscheider (Acta Carsologica, 2010)

Intermediate result: Present state and retreat of the glacier

State in 2008:

- Volume: 1.0 x 10^8 m^3
- Surface area: 2.8 km^2

Annual ice loss:

- Thickness: ca. 1.5 m
- Length: ca. 20 m
- Volume: 4.2 x 10^6 m^3

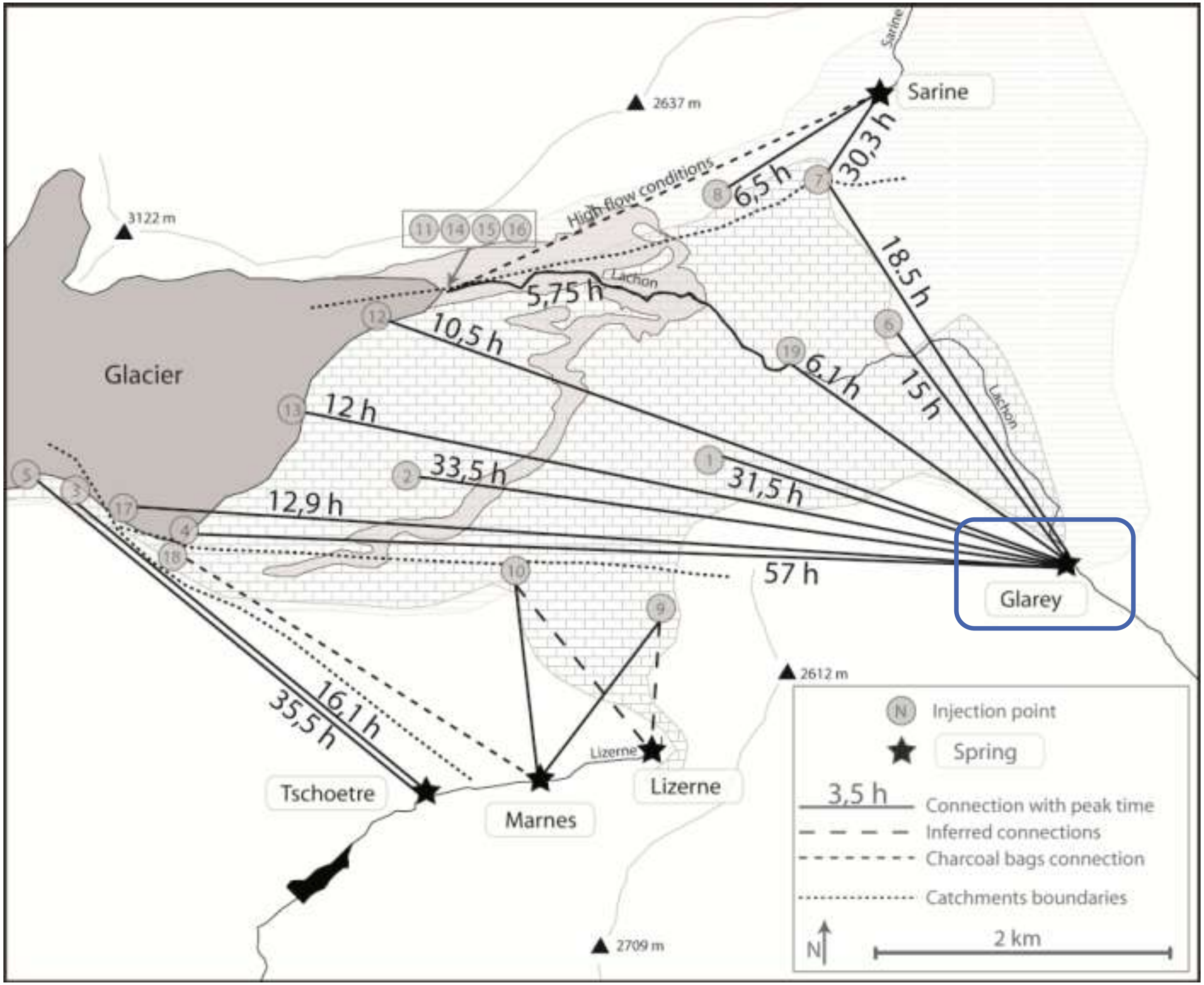
If this trend continues, all or most of this glacier will have vanished in ca. 20 to 30 years (while most large alpine glaciers will shrink but still exist).

Sinking meltwater at the glacier front

Photo: G. Favre

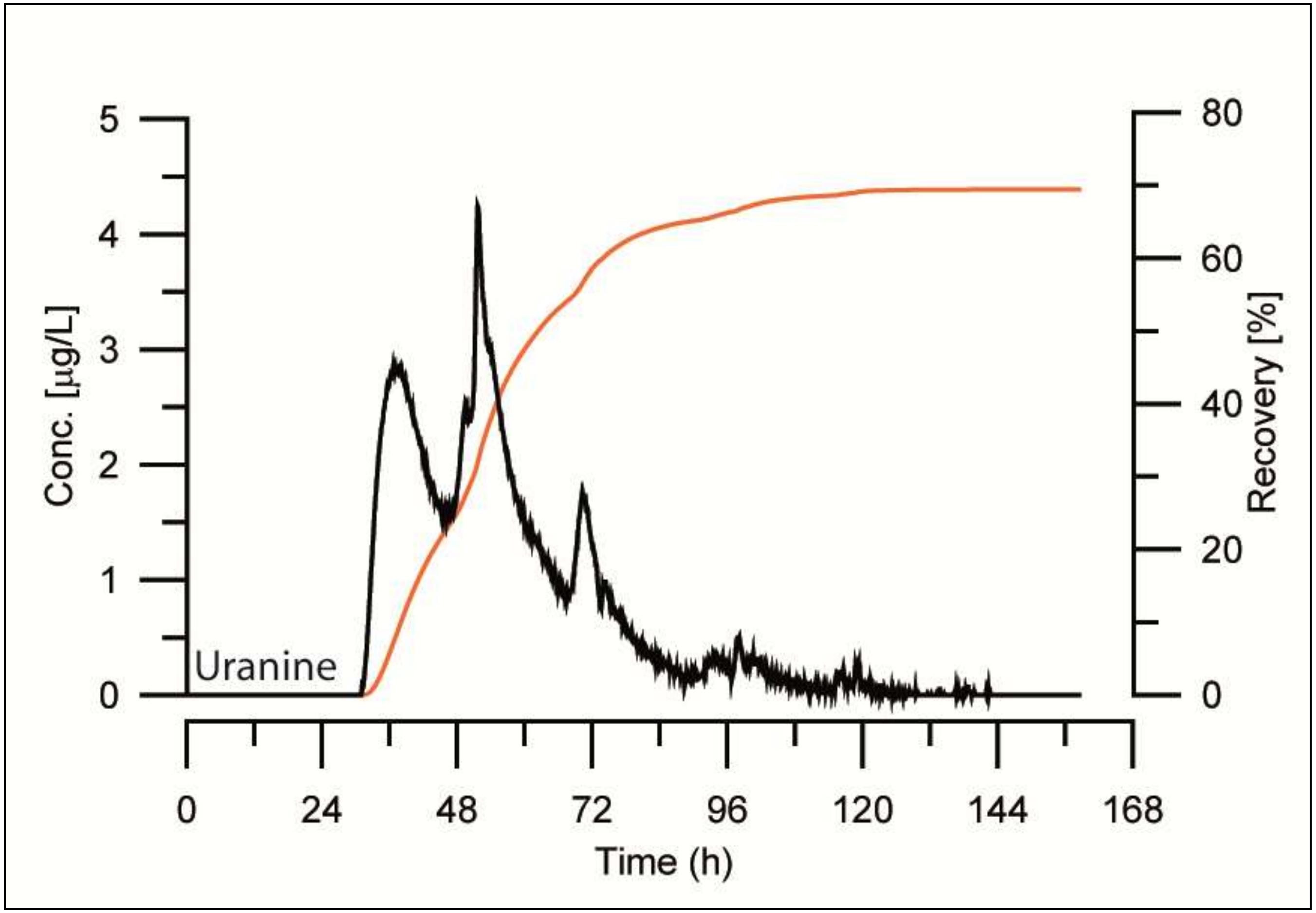
19 tracer injections into the karst aquifer

Results of the 19 tracer injections



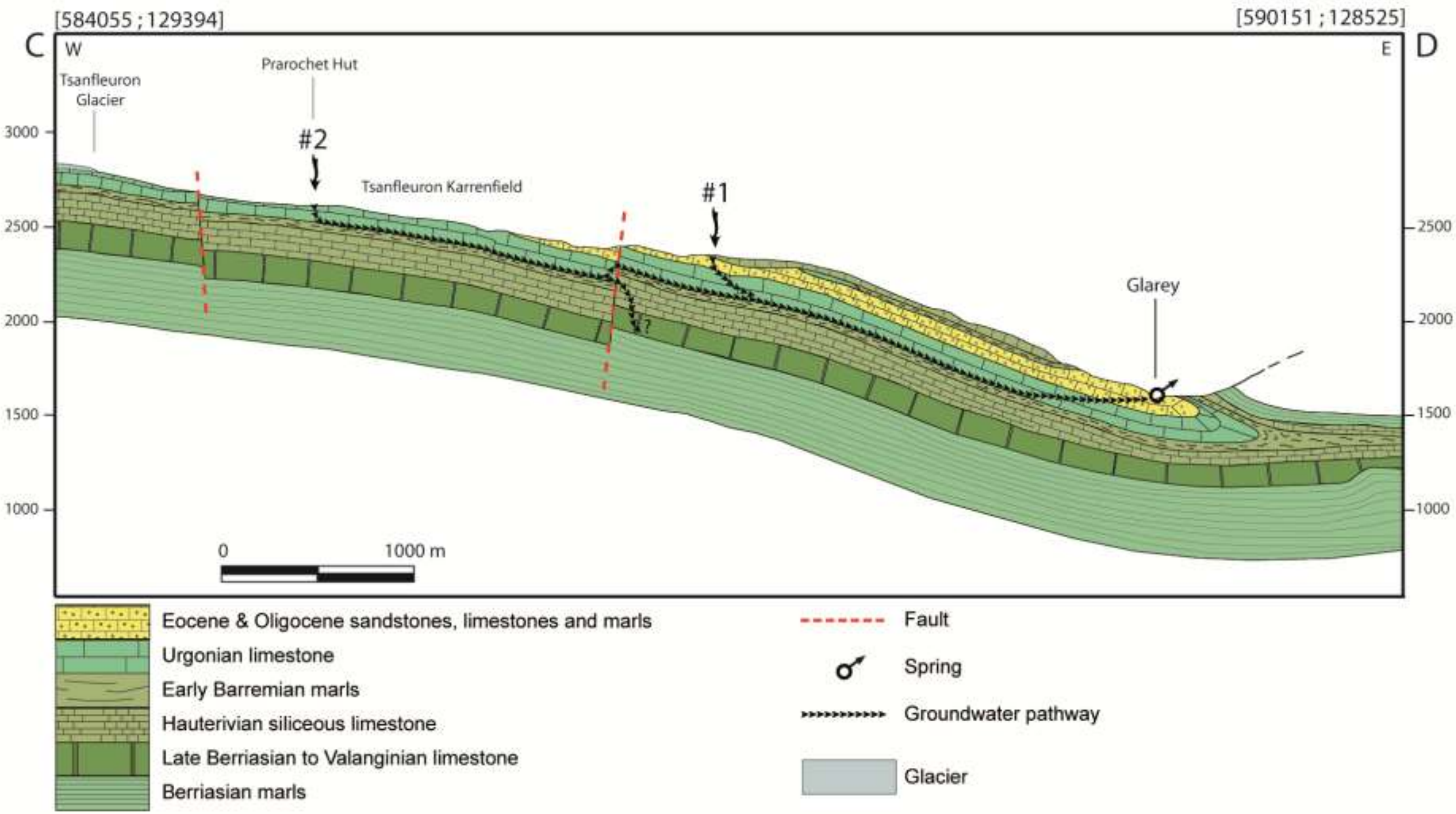
Gremaud, Goldscheider et al. (2009)

Example of a tracer breakthrough curve



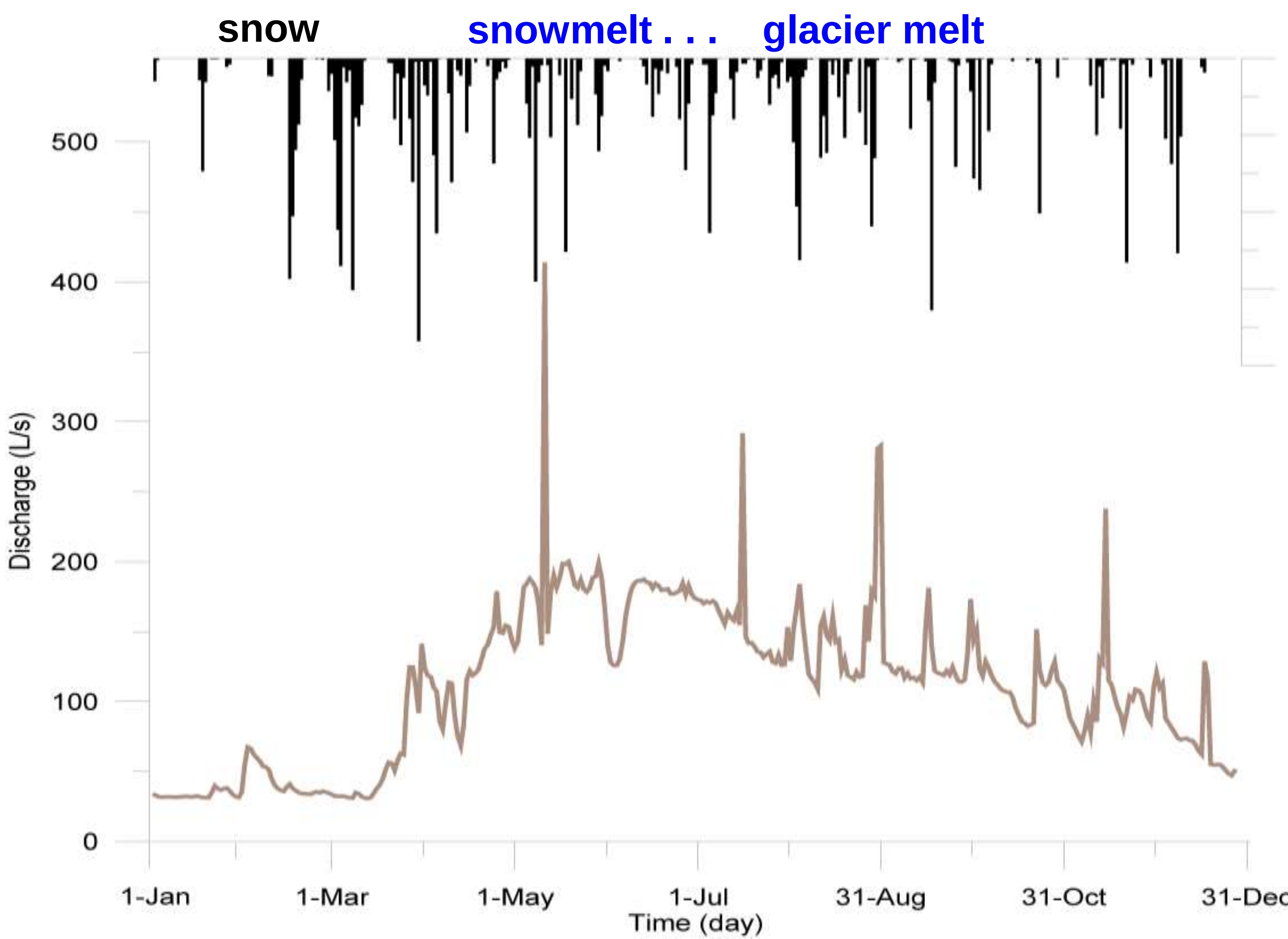
Influence of diurnal variations of glacial meltwater production on the shape of the tracer breakthrough curve

Flowpaths towards Glarey spring: parallel to stratification, in karst limestone on top of marl



Gremaud, Goldscheider et al. (2009)

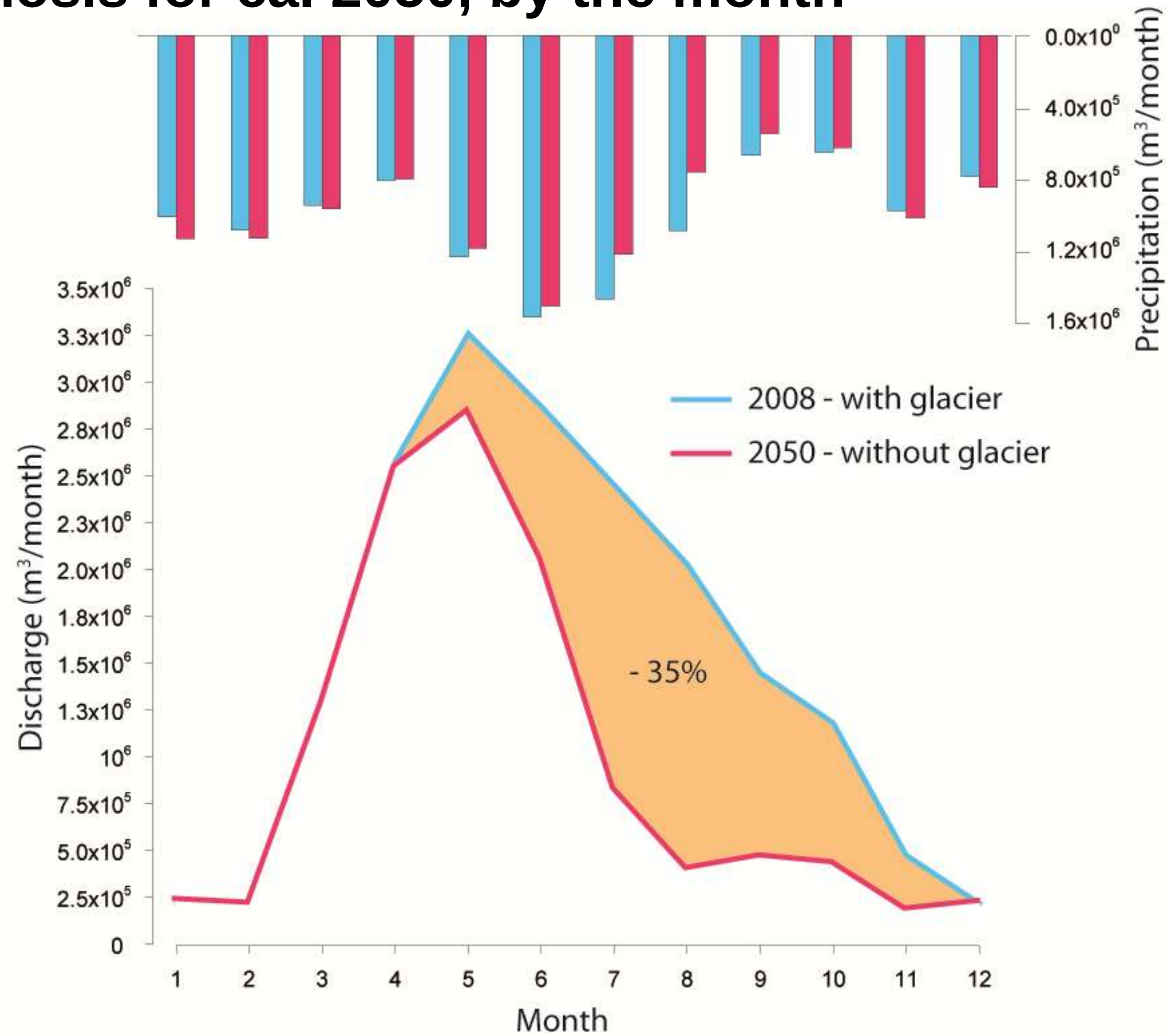
Observed annual variability



Attempt of a Prognosis for 2030-2050

- If the current trend continues, the glacier would vanish by ca. 2030-2050 (uncertain but realistic).
- The current annual ice loss corresponds to a freshwater volume of ca. 3.9×10^6 m^3 / year.
- Annual discharge of Glarey spring: 2.1×10^7 m^3 / year.
- Based on these numbers, 20 % of the spring discharge results from glacier retreat (other methods suggest even 35 %).
- This quantity will be missing when the glacier has disappeared.
- Spring discharge will decrease in summer and autumn, while less change is expected during winter and springtime.

Prognosis for ca. 2050, by the month



Gremaud & Goldscheider, in preparation

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… and others


Thank you for your attention
Photo: N. Goldscheider